Using Analogs for Performance Testing of Humans in Spacesuits in Simulated Reduced Gravity

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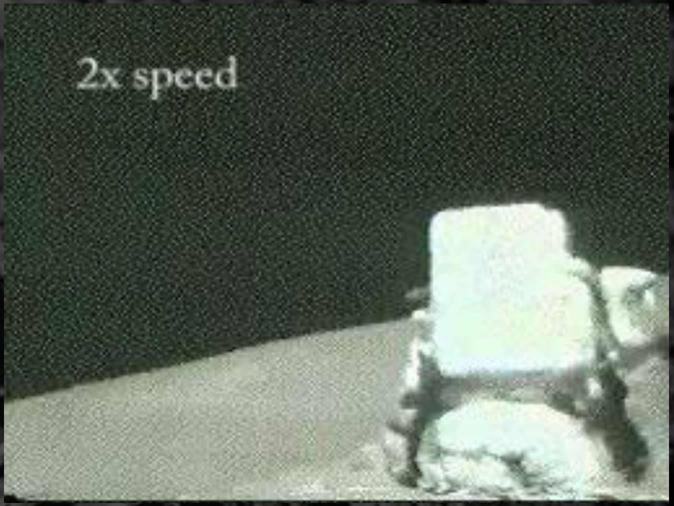
The Challenge of Moving Past Apollo

- Apollo was a remarkable human achievement, however fewer than 30 total program EVAs
- Both surface crew performed EVA, but a maximum of 3 EVAs per mission
- Exploration missions forecast 100s to 1000s of EVAs per mission
- Limited mobility, dexterity, center of gravity and other features of the suit required significant crew compensation to accomplish the objectives. It would not be feasible to perform the Exploration EVAs using Apollo vintage designs
- The vision is to develop an EVA system that is low overhead and results in close to (or better than) 1-g shirt sleeve performance i.e. “ A suit that is a pleasure to work in, one that you would want to go out and explore in on your day off”
- Planetary EVA will be very different from Earth orbit EVA – a significant change in design and operational philosophies will be required to optimize suited human performance in partial gravity
- Unlike Shuttle & ISS, all Exploration crewmembers must be able to perform EVA – and suits must be built to accommodate and optimize performance for all crew



HRP/EVA Discipline & Engineering/EVA Systems

HRP: Provides health and performance expertise on what the human requires

Engineering: Working with HRP, determines what the system shall provide for the human

- Biomechanics
- Human Factors
- Suit Trauma/Injury Prevention
- Thermal & Metabolic
- Space Medicine
- Sensorimotor
- Radiation Protection
- DCS Protection
- Nutrition
- Bone & Muscle
- Exercise Physiology

Recommendations for:

- Optimal Suit Weight, Mass, Pressure, CG and Kinematics
- Suit Trauma Countermeasures
- Contingency Reponses *(Walkback, Suit Leak, Degrade Cooling)*
- Consumables, Usage & Management
- Biomedical Sensors and algorithms
- Validated Prebreathe Protocols
- Nutrition & Hydration Systems
- Waste Management System
- Exercise Countermeasure of EVA

Integrated Suit Testing Research Plan *Concept*

1.0 Inputs to IST
- Ops & Engineering Concepts
  - Suit Designs
  - Architectures
  - Mission Objectives
  - Specific EVA Tasks
- Stakeholder Objectives
  - HRP, Analogs, Exploration
- Requirements TBD's

2.0
Develop Analog Facilities & Evaluation Techniques

3.0
Physiological, Biomechanical & EVA Hardware Testing

4.0
Performance Data for EVA

5.0
IST Data Discussions & Lessons Learned

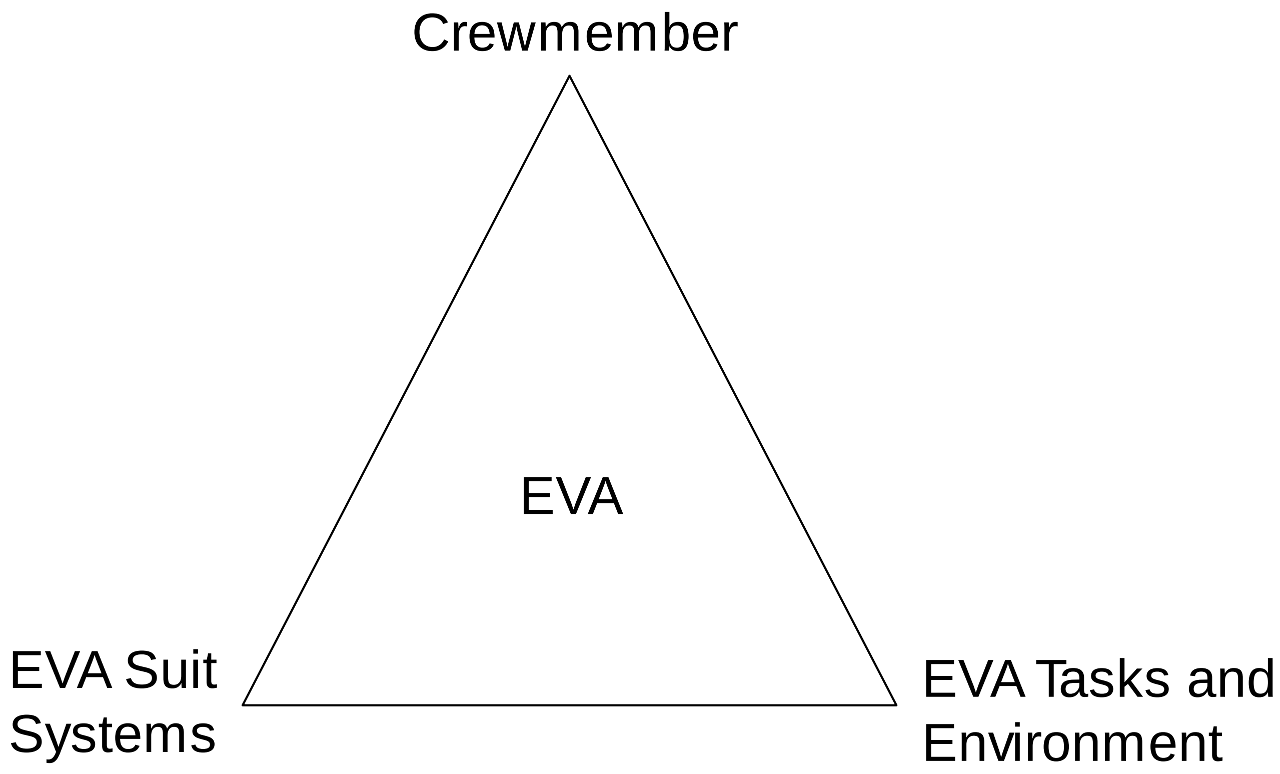
IST Team Consensus

7.0
Provide inputs for requirement development and verification
- NASA Standard 3001
- Human Systems RB
- Exploration Analogs & Mission Development
- Other Orgs as Required

IST Team Consensus

6.0
Products / Deliverables
- Test Reports / Presentations
- Model Development
- Inputs to Other Risks

EVA Interactions (Example)



Current NASA STD 3001 Volume 1 - Aerobic Capacity Standard

4.2.3 Fitness-for-Duty Aerobic Capacity Standard

4.2.3.1 Crewmembers shall have a pre-flight maximum aerobic capacity (VO_2max) at or above the mean for their age and sex (see American College of Sports Medicine Guidelines (ACSM)), in table 1 below).

Table 1—50th Percentile Values for Maximal Aerobic Power ($ml \cdot kg^{-1} \cdot min^{-1}$)

Age	Men	Women
20-29	43.5	35.2
30-39	41.0	33.8
40-49	38.1	30.9
50-59	35.2	28.2
60+	31.8	25.8

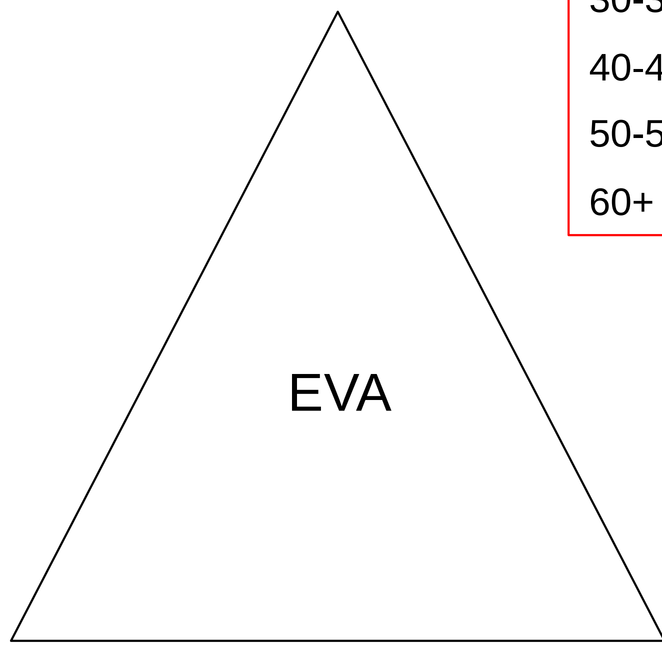
4.2.3.2 The in-flight aerobic fitness shall be maintained, either through countermeasures or work performance, at or above 75 percent of the pre-flight value, as determined by either direct or indirect measures.

4.2.3.3 The post-flight rehabilitation shall be aimed at achieving a VO2max at or above the mean for age and sex (see ACSM's Guidelines in table 1).

EVA Interaction Triangle (Example)

Age	Men	Women
20-29	43.5	35.2
30-39	41.0	33.8
40-49	38.1	30.9
50-59	35.2	28.2
60+	31.8	25.8

Crewmember



EVA Suit Systems

EVA Tasks and Environment

MKIII Suit Design mass ~ 120 kg

Walking 2.5 mph on surface

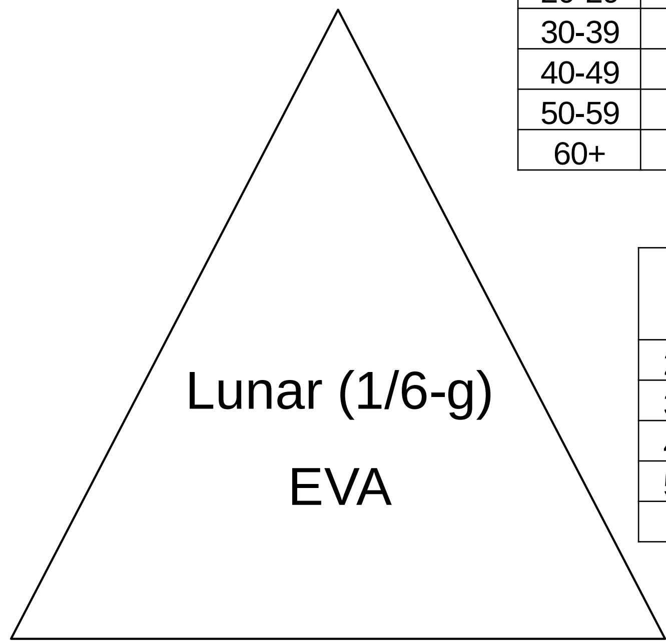
EVA Interaction Triangle (Example)

Crewmember

Age	Men (VO_2max)	% max	Women (VO_2max)	% max
20-29	43.5	46%	35.2	57%
30-39	41	49%	33.8	59%
40-49	38.1	52%	30.9	65%
50-59	35.2	57%	28.2	71%
60+	31.8	63%	25.8	78%

<u>With allowable deconditioning</u>

Age	Men (VO_2max)	% max	Women (VO_2max)	% max
20-29	32.6	61%	26.4	76%
30-39	30.8	65%	25.4	79%
40-49	28.6	70%	23.2	86%
50-59	26.4	76%	21.2	95%
60+	23.9	84%	19.4	103%



EVA Suit Systems

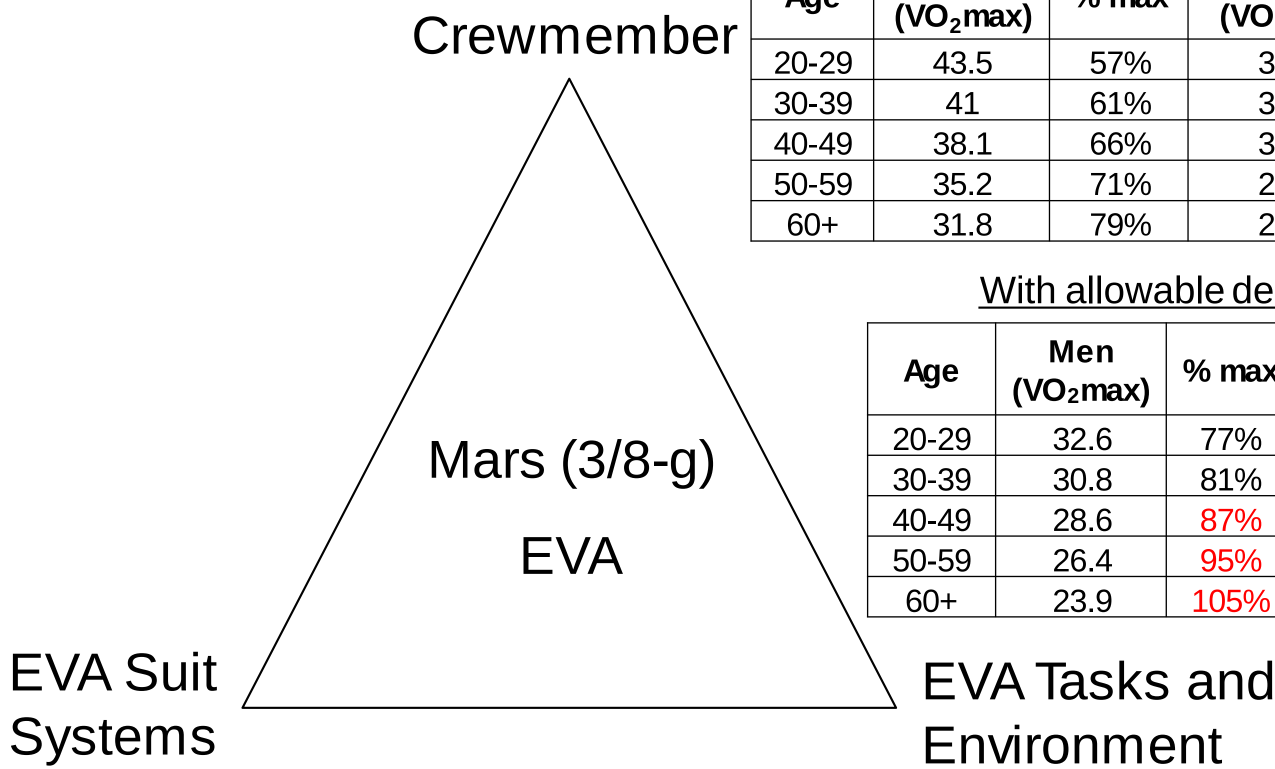
EVA Tasks and Environment

MKIII Suit Design mass ~ 120 kg*

Walking 2.5 mph on surface ~ 20 ml/min/kg*

* Source: EVA Walkback Test Report, NASA/TP–2009–214796

EVA Interaction Triangle (Example)



Age	Men (VO_2max)	% max	Women (VO_2max)	% max
20-29	43.5	57%	35.2	71%
30-39	41	61%	33.8	74%
40-49	38.1	66%	30.9	81%
50-59	35.2	71%	28.2	89%
60+	31.8	79%	25.8	97%

With allowable deconditioning

Age	Men (VO_2max)	% max	Women (VO_2max)	% max
20-29	32.6	77%	26.4	95%
30-39	30.8	81%	25.4	99%
40-49	28.6	87%	23.2	108%
50-59	26.4	95%	21.2	118%
60+	23.9	105%	19.4	129%

MKIII Suit Design mass ~ 120 kg*

Walking 2.5 mph on surface ~ 25 ml/min/kg*

* Source: EVA Walkback Test Report, NASA/TP–2009–214796

Options

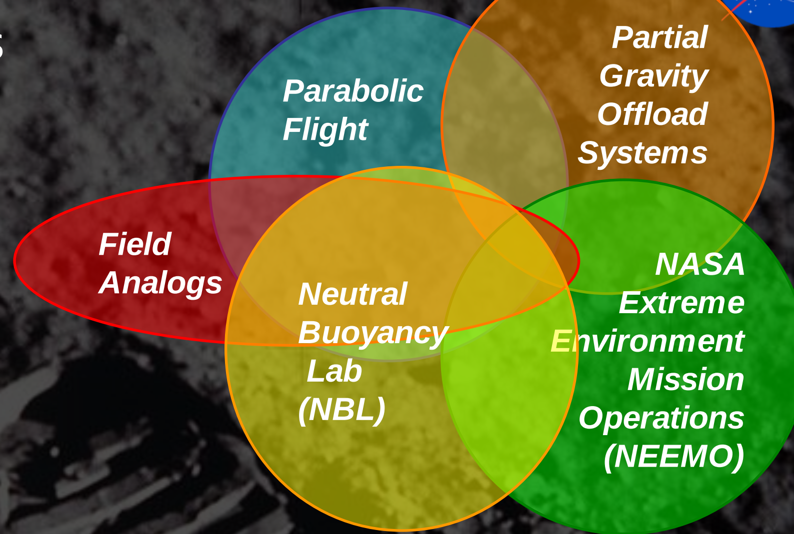
- Update aerobic capacity standard
- Walk slower (need data on other walking speeds)
- Reduce suit mass or improve walking mobility (need data on how other suit masses and suit mobility systems affect human metabolic rate)
- Eliminate walking as an EVA task

Which one of these is the correct answer?

- Without collaborative research, we cannot know.

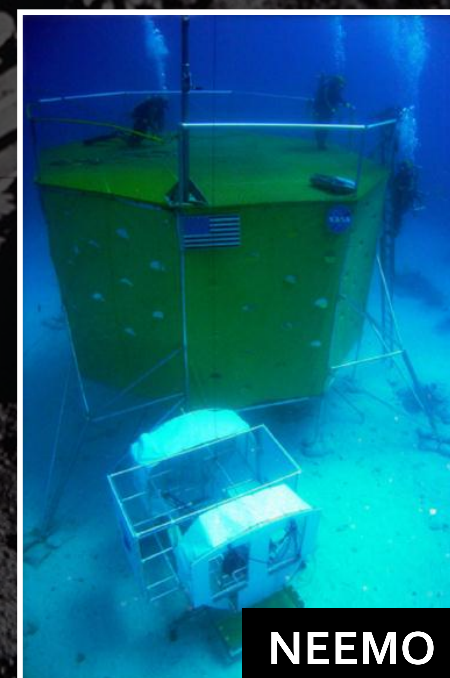
Testing in Analog Environments

- Tests are performed in multiple analogs, as each environment has limitations for simulating partial gravity and representing a realistic operational environment




Parabolic Flight


Offload Systems


NEEMO


NBL

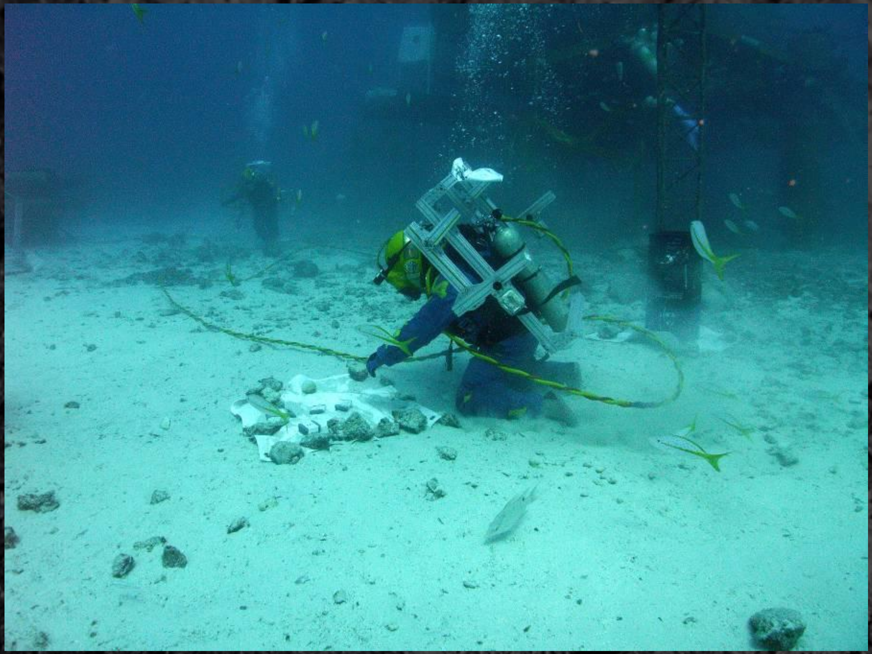

1-g Field Analogs

Parabolic Flight

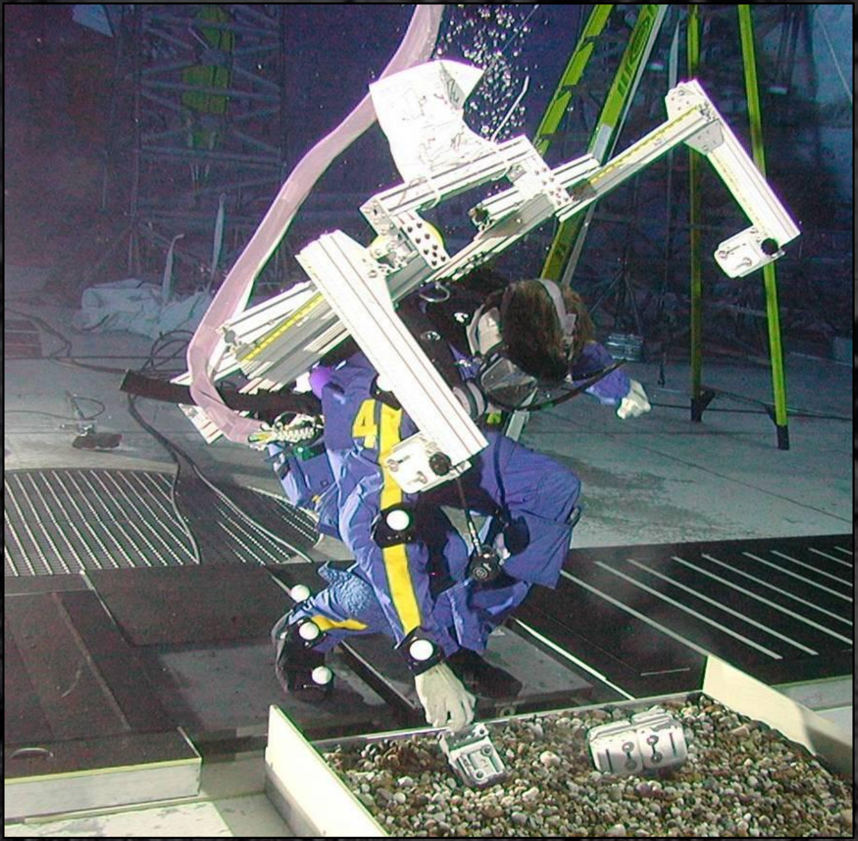
POGO Testing with MKIII

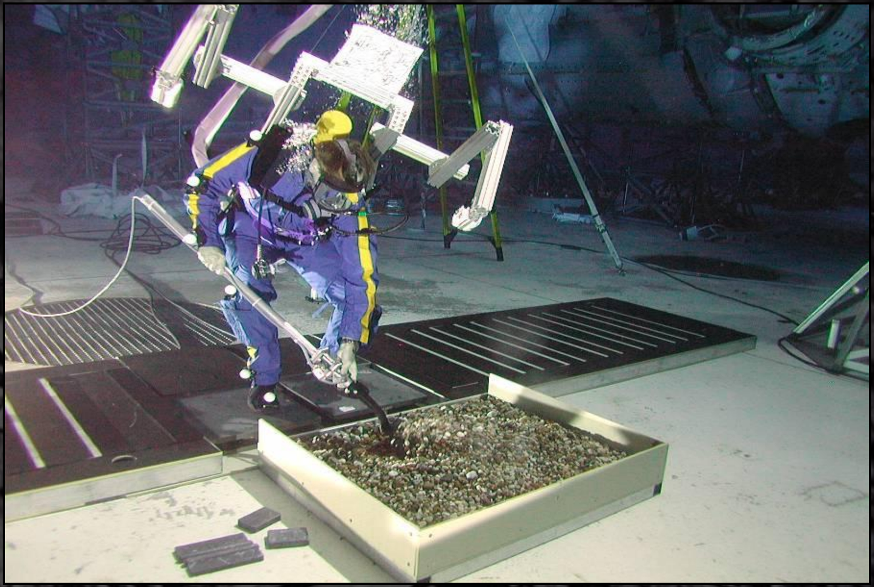
Haughton Mars Project

NEEMO – CG Testing



NBL CG Testing





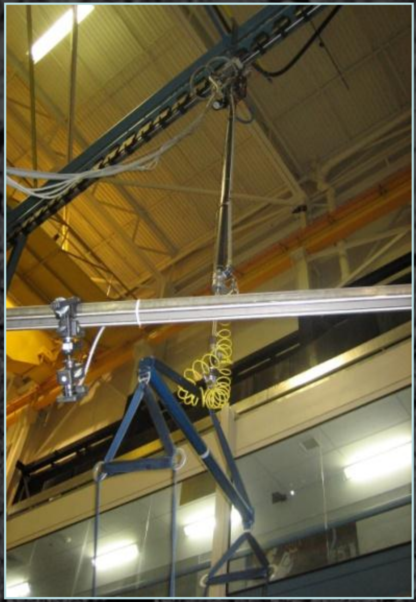
Integrated EVA Suit Testing Analog Objectives

1. To define the usability and limitations of partial-gravity analogs for EVA applications
   - Overhead Suspension Offload Systems
   - Parabolic Flight
   - Underwater
   - 1-g Field Analogs
2. To define standard measures and protocols for objectively evaluating future exploration suit candidates and requirements verification of the flight suit

Going in, we understood that all analog environments have certain limitations and our goal was to perform similar tests across different environments to better understand the strengths and limitations of each analog environment

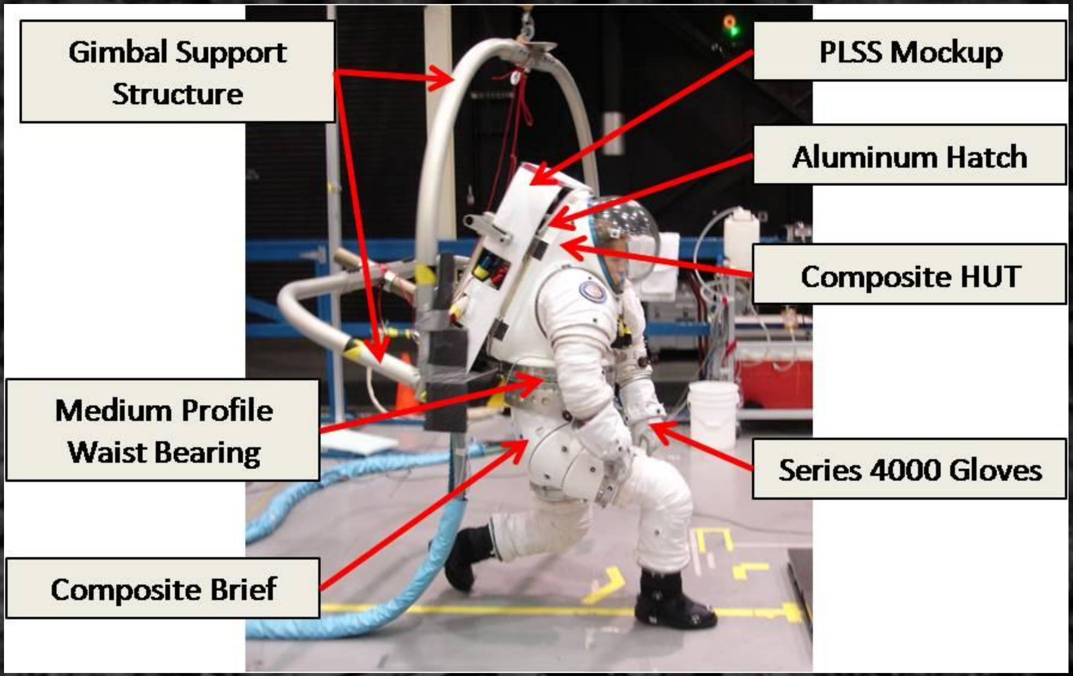
IST Hardware

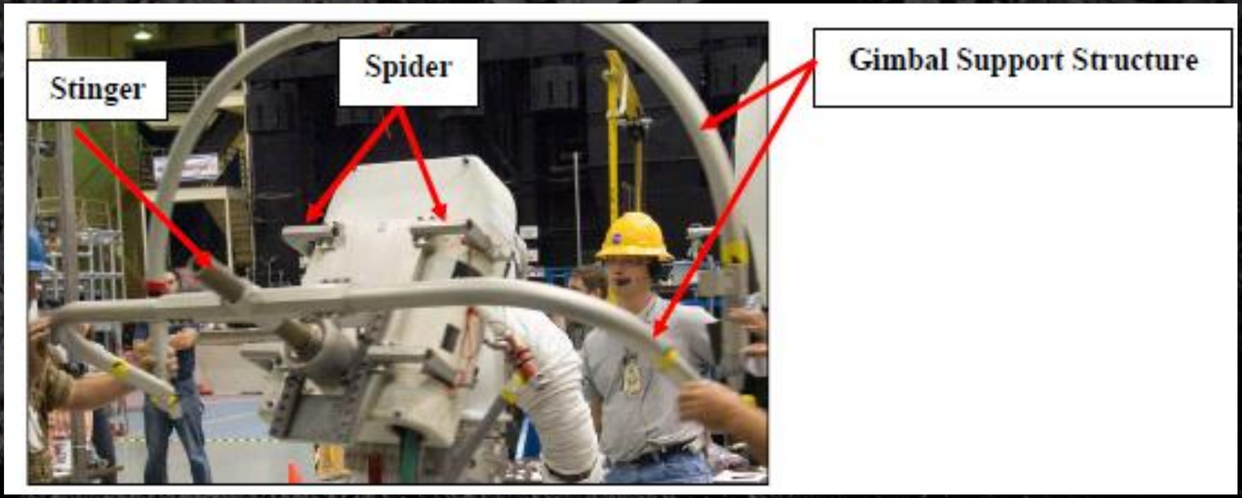
- Partial gravity simulator (POGO)
  - Overhead suspension
  - A-frame with 2 translational DOF
  - Spider/gimbal attachment for suited tests
  - Spreader-bar and harness for unsuited tests



IST Hardware

- MKIII EVA Suit
  - Hybrid of hard (torso/brief) and soft (arms/legs) components
  - Multi-axial mobility for planetary environments
  - 121 kg total suit mass





Human Performance Testing Series
Detailed Objectives & Measurements

Identify the relative contributions of weight, pressure, and suit kinematics to the overall metabolic cost of the MKIII suit in its POGO configuration in lunar gravity

To quantify the effects of varied gravity, varied mass, varied pressure, varied cg, and suit kinematic constraints on human performance

To develop predictive models of metabolic rate, subjective assessments, and suit kinematics based on measurable suit, task, and subject parameters

Human Performance Measurements Collected:

- Metabolic Rate
- CO_2 and humidity produced
- Body heat production & storage
- Human kinematics (range of motion, joint cycles)
- Gait parameters
- Subjective measurements of perceived exertion, comfort, and gravity compensation
- Ground Reaction Forces (from surface contact)

Integrated Suit Test 1

<u>Specific Objectives:</u>

- Quantify effects of the following factors on metabolic rates in the suit:
  - 1) Weight/Gravity
  - 2) Pressure
  - 3) Inertial mass
  - 4) Waist-locked vs waist-unlocked
- Level ambulation at varying speeds only

Stage	Speed
1	PTS minus 2.4 km·h^{-1}
2	PTS minus 1.6 km·h^{-1}
3	PTS minus 0.8 km·h^{-1}
Preferred Transition Speed (PTS) Range of Speeds:	
4	PTS plus 0.8 km·h^{-1}
5	PTS plus 2.4 km·h^{-1}
6	PTS plus 4.0 km·h^{-1}

Effect of Gravity on Ambulation

Suit / Shirt-Sleeve Testing Protocols for IST-2

- Varied Gravity
  - 0.12, 0.17, 0.22, 0.27 & 0.32-g
  - Constant suit mass (121 kg)
  - Constant suit pressure (4.3 psid)
  - Matched shirt-sleeve controls at 0.12, 0.17 and 0.22-g
- Varied Pressure
  - 1.0, 3.0, 4.3, 5.0 & 6.5 psid
  - Constant suit mass/weight (121 kg/0.17-g)
- Varied Inertial Mass (shirt-sleeve)
  - Constant weight
  - 25, 50, 75 lbs added mass
- Waist-locked
  - Compared to standard MKIII configuration
  - 121 kg suit mass, 0.17-g, 4.3 psid

Protocols and Data Collection

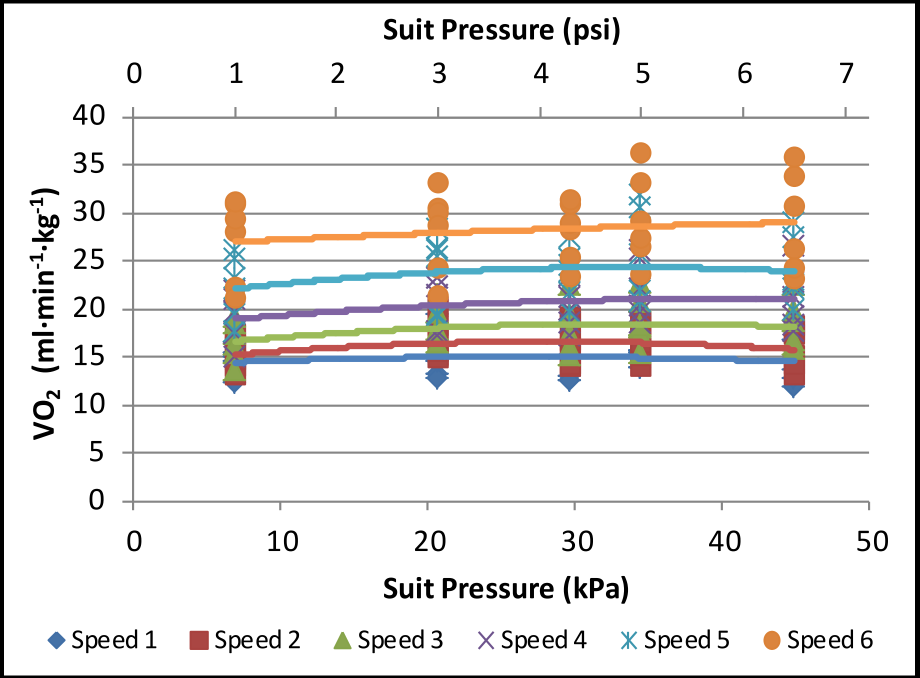
- Shoveling, rock transfer, busy board
  - Metabolic Rate (VO_2)
  - Gravity Compensation and Performance Scale (GCPS)
  - Rating of Perceived Exertion (RPE)
  - Motion Capture
  - Ground Reaction Force
- Rock pickup, kneel and recover, hammering, ladder setup
  - GCPS
- Incline Treadmill Walking
  (10,20,30% at slowest walking speed)
  - VO_2
  - GCPS, RPE
  - Motion Capture
  - Gait Parameters
  - Ground Reaction Force

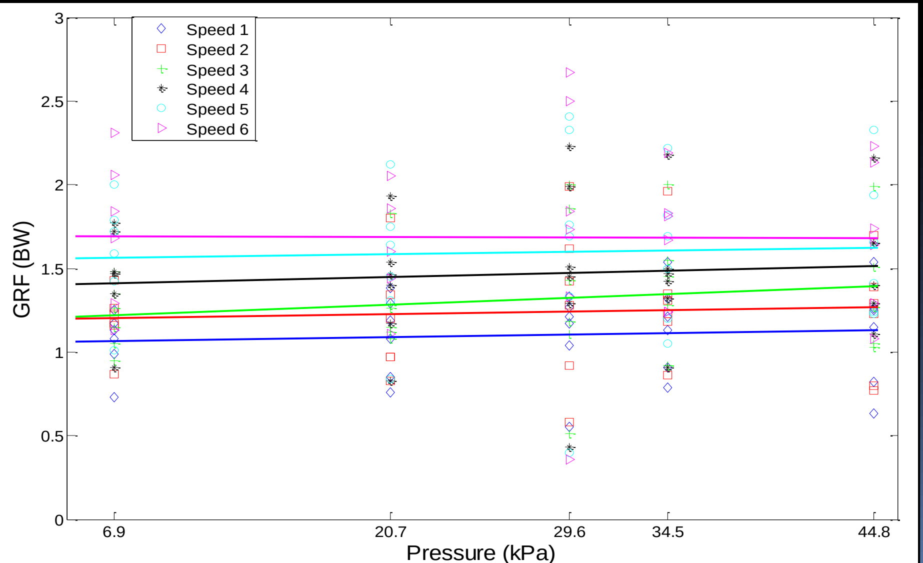
Suited Human Performance Objectives

1. To determine how the following factors affect human performance during ambulation and exploration tasks:
   - Suit pressure
   - Mass / weight / gravity level
   - Center of gravity
   - Locking the waist bearing*
     - Only done at POGO configuration at lunar gravity (121 kg system mass, 29.6 kPa)
2. Understand specific human performance limitations of a suit compared to shirt-sleeve controls

∆ Pressure Results (POGO)

- Little to no effect on most human performance metrics including:
  - Metabolic rate
  - GRF
  - GCPS & RPE
  - Gait parameters
- Joint kinematics showed no consistent trends



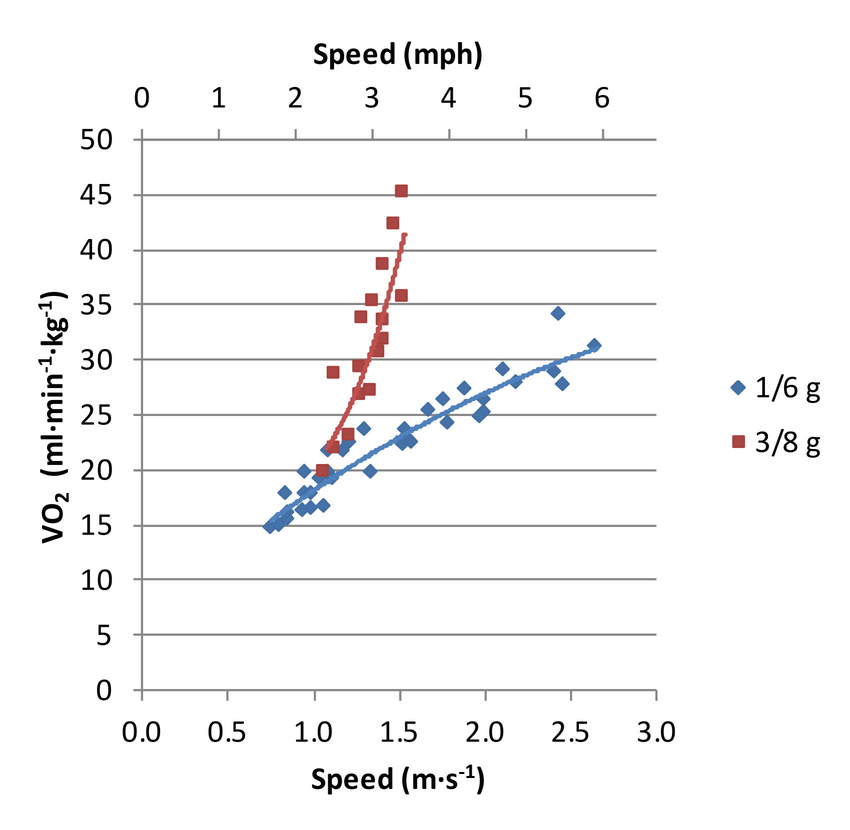


Mass / Weight / Gravity Background

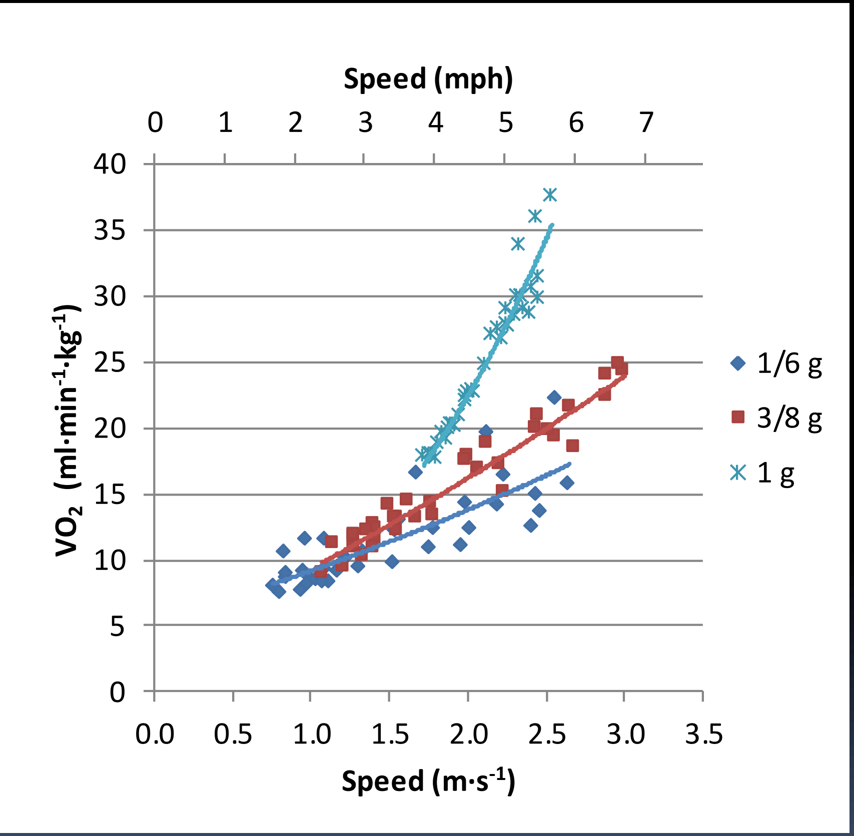
- Human performance would be expected to vary as gravity changes (1/6 *g*, 3/8 *g*, 1 *g*)
- Suit mass is expected to be an important factor affecting human performance but testing this hypothesis was difficult
  - POGO has limited lift capacity (400-500 lb)
  - MKIII was only suit available for testing
    - Due to these limitations, we wanted to see if suit mass could be simulated by a change in system offload, therefore changing the total gravity adjusted weight (TGAW)
    - TGAW = System Mass x Gravity Level = **Weight on Ground**
    - System mass includes subject, suit and gimbal hardware

Δ Gravity Results (POGO)

Suited Metabolic Rates



Unsuited Metabolic Rates



- As gravity ↑, metabolic rate ↑
- Difference between gravities is greater as speed ↑ and when suited
- Similar findings with RPE, GCPS and GRF

Mass/Weight/Gravity Test Design (POGO)

Δ Weight (Simulated Mass) Testing

(Suited and Unsuited)

- Constant Factors
  - Mass
  - CG
  - Moment of inertia
- Varied Factors
  - Offload (gravity)/weight

Δ Mass Testing

(Unsuited Only)

- Constant Factors
  - Weight
  - CG
  - Moment of inertia
- Varied Factors
  - Offload (gravity)
  - Mass

Force = Mass * Acceleration
Weight = Mass * Gravity

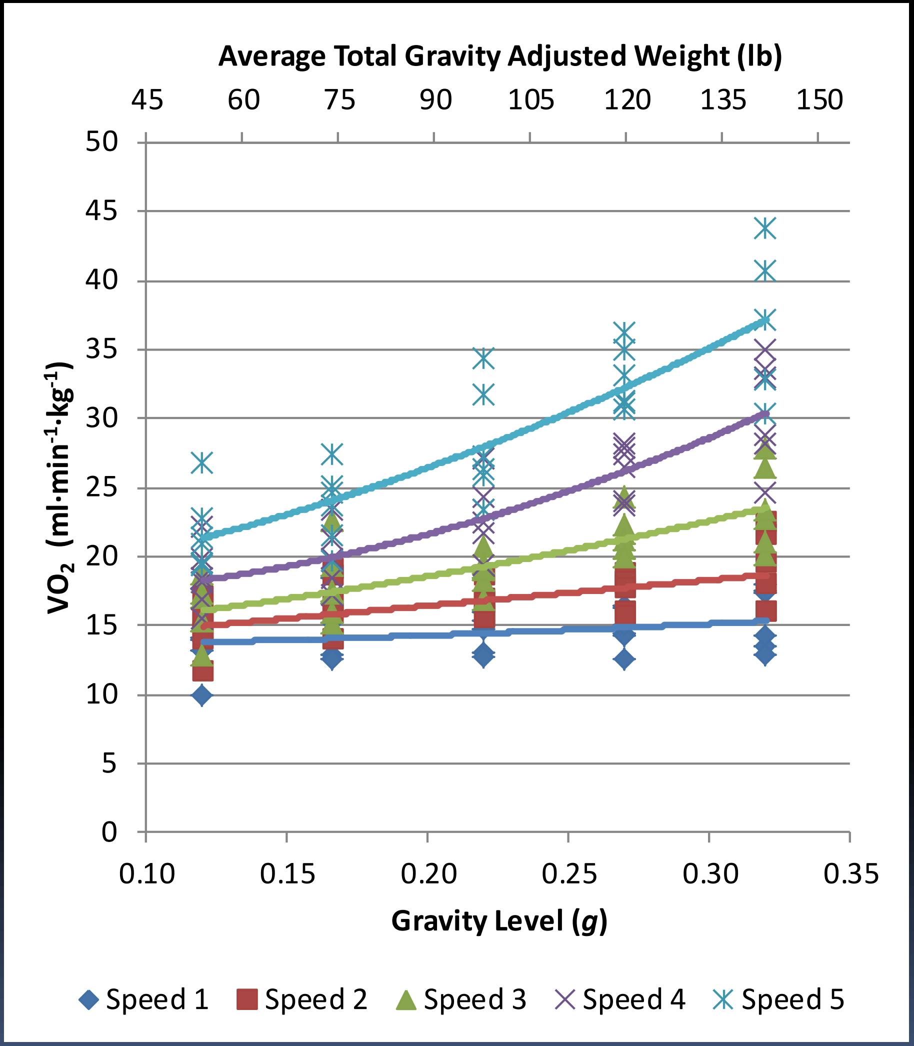
∆ Weight (Simulated Mass) Test Design (POGO)

Subject Mass (kg)	Suit/Gimbal Mass (kg)	Gravity Level (g)	Total Gravity Adjusted Weight (TGAW)*	Comments
80	121	0.17	329 N (74 lb)	Standard POGO lunar configuration
Subject Mass (kg)	**Suit/Gimbal Mass (kg)**	**Gravity Level (g)**	**TGAW**	**Comments**
80	121	**0.12**	236 N (53 lb)	Offload was adjusted and as a result, the total gravity adjusted weight increased as gravity increased
80	121	**0.22**	431 N (97 lb)	
80	121	**0.27**	529 N (119 lb)	
80	121	**0.32**	631 N (142 lb)	
Same data but 2 different ways of looking at it (initial assumption is both are valid)				
Subject Mass (kg)	**Simulated Suit/Gimbal Mass (kg)**	**Assumed Gravity Level (g)**	**TGAW**	**Comments**
80	**63**	0.17	236 N (53 lb)	Focus in on lunar gravity, we assume that the only way to get different TGAW on the Moon would be to change the suit or subject mass
80	**185**	0.17	431 N (97 lb)	
80	**245**	0.17	529 N (119 lb)	
80	**306**	0.17	631 N (142 lb)	

*Total Gravity Adjusted Weight (TGAW) = System Mass x Gravity Level = **Weight on Ground**

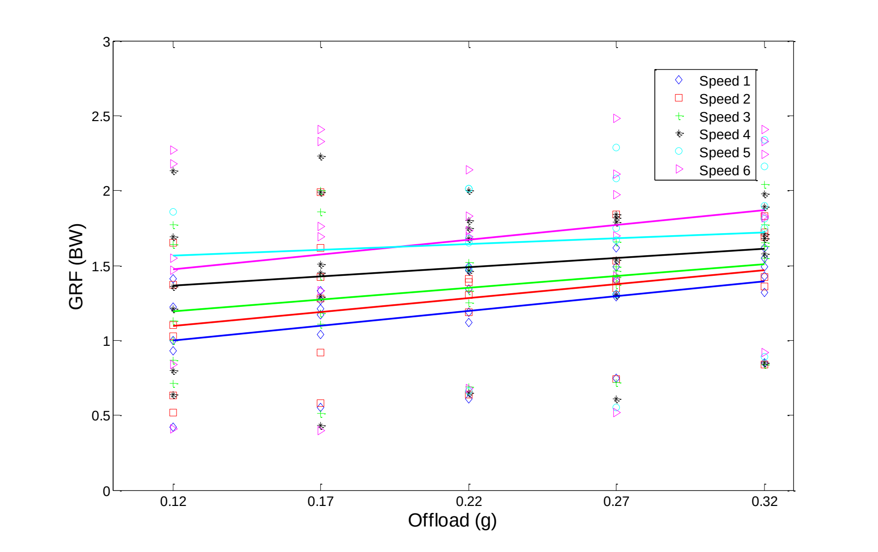
Δ Weight (Simulated Mass) Results (POGO)

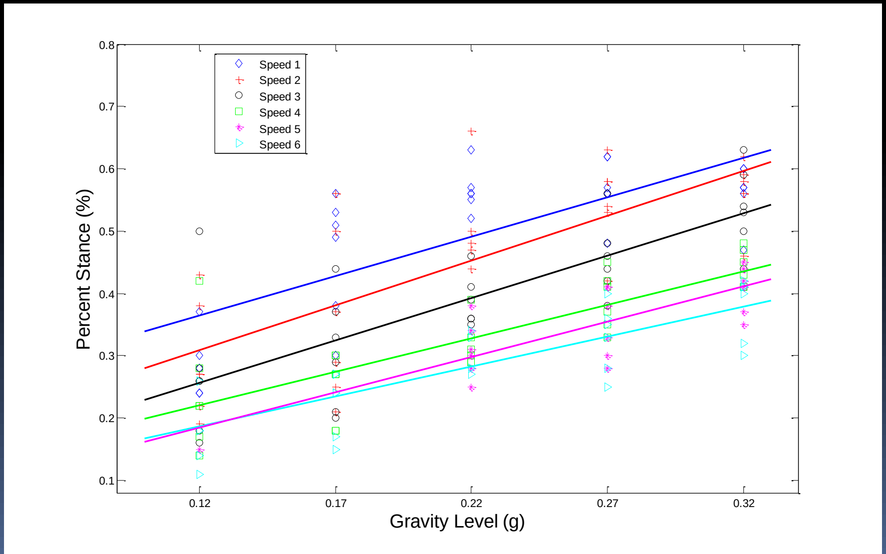
- Significant effect on most metrics
- Task dependent
- Ambulation results with ↑ weight
  - Metabolic rate ↑
  - RPE / GCPS ↑
  - Unsuited results were similar



∆ Weight (Simulated Mass) Results (POGO)

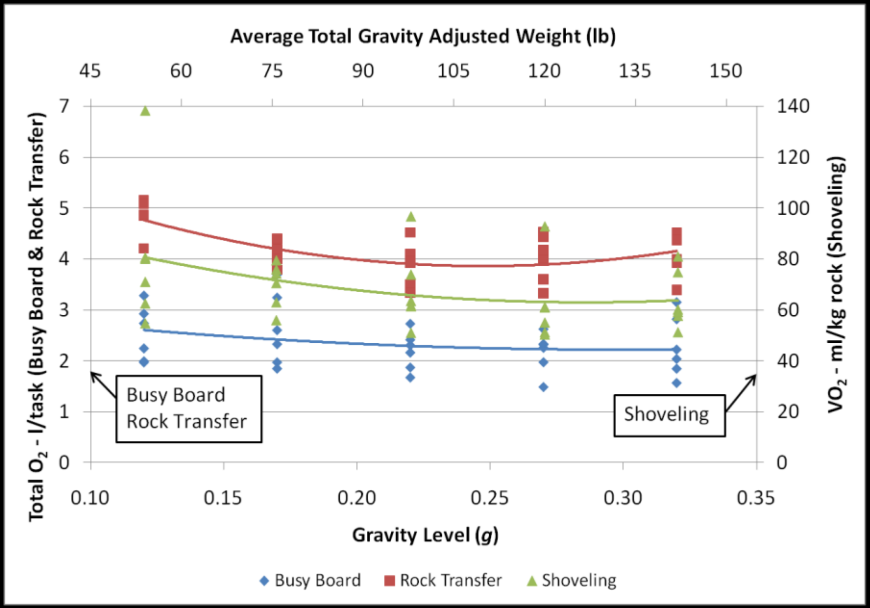
- Ambulation results with ↑ weight
  - GRF ↑ as expected
  - Gait parameters respond as expected
    - Shorter, more frequent steps with ↑ time on ground

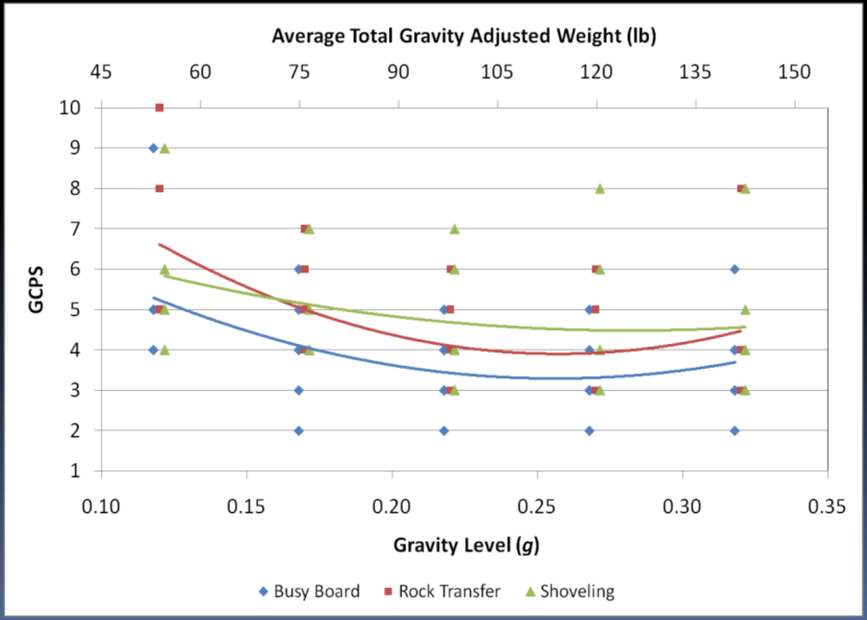




∆ Weight (Simulated Mass) Results (POGO)

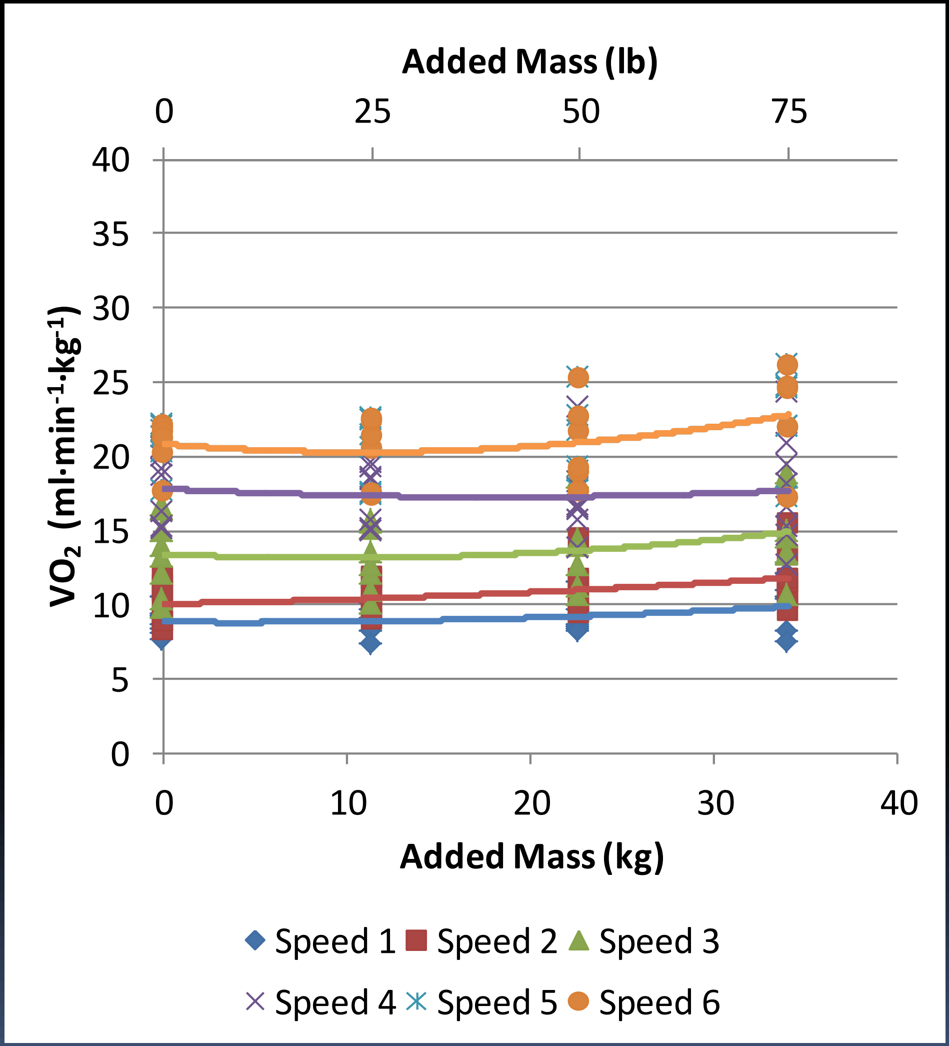
- Exploration task results with ↑ weight
  - Results were similar for metabolic rate, GCPS and center of pressure (COP) for exploration tasks
  - Difference between 0.12 and 0.17 *g* was greatest with little difference between 0.17 through 0.32 *g*
  - Indicates that more weight (up to a certain point) leads to improved performance
    - Unexpected finding
    - Is this valid conclusion?





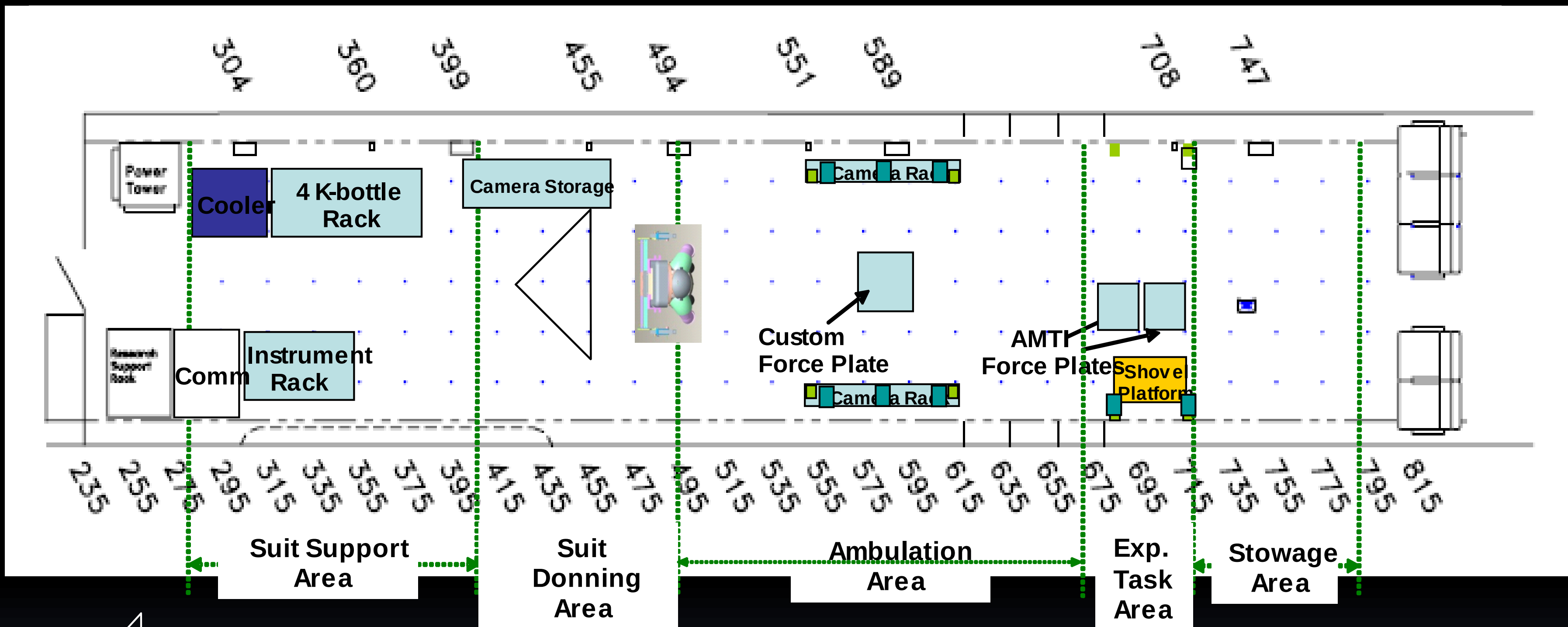
∆ Mass Results (POGO)

- Unsuited testing only
  - Constant ground weight was maintained (i.e., add 11 kg then offload it)
- Mixed trend lines
- Limited mass variability (0-34 kg)
- Extrapolating out to 121 kg suit produced unrealistic numbers
- Spreader bar harness may contribute to data inconsistencies



Parabolic Flight Testing

Original Phase I C-9 Layout



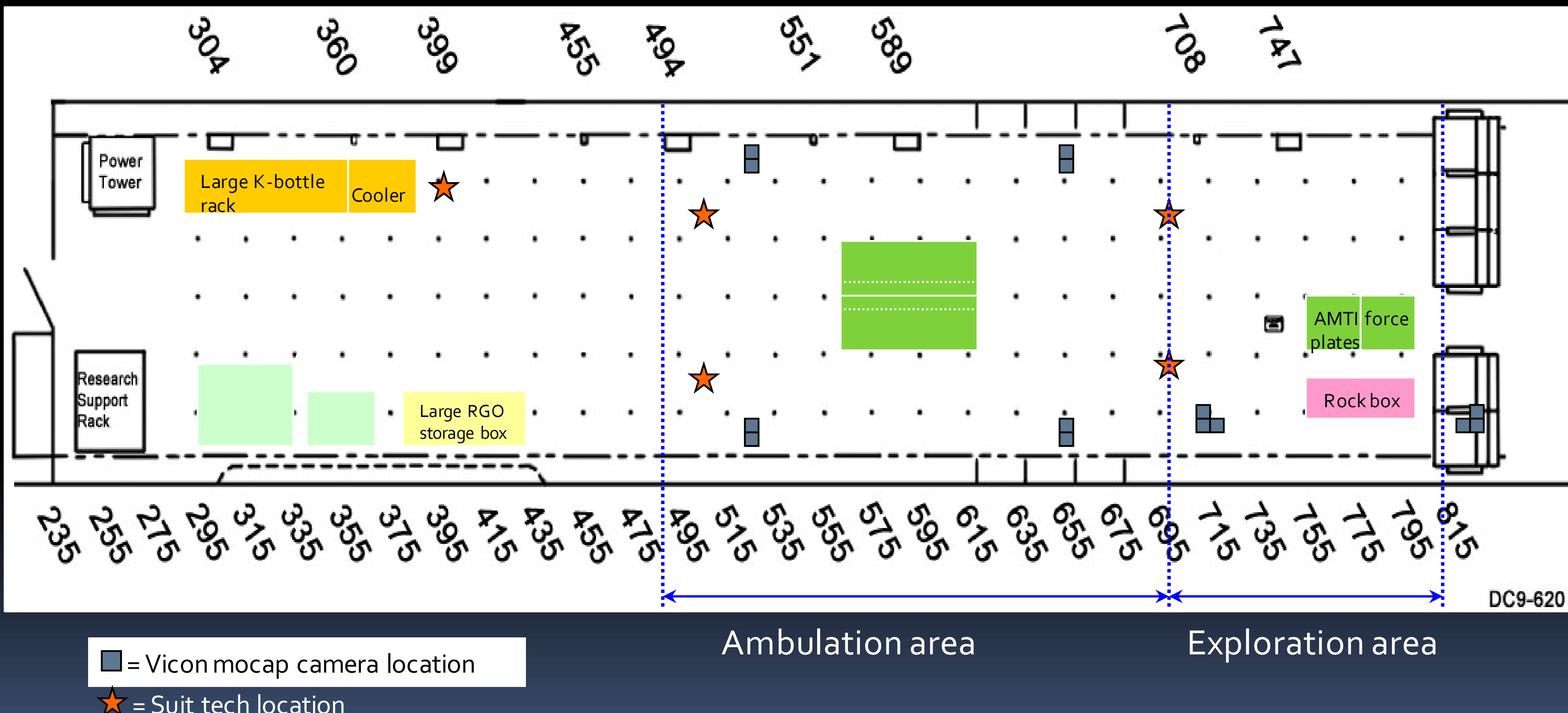
= MK III Donning Stand

= Motion Capture Cameras

Note: MK III umbilicals will be stored in the cooler for take off and landing

Modified Phase II C-9 Layout

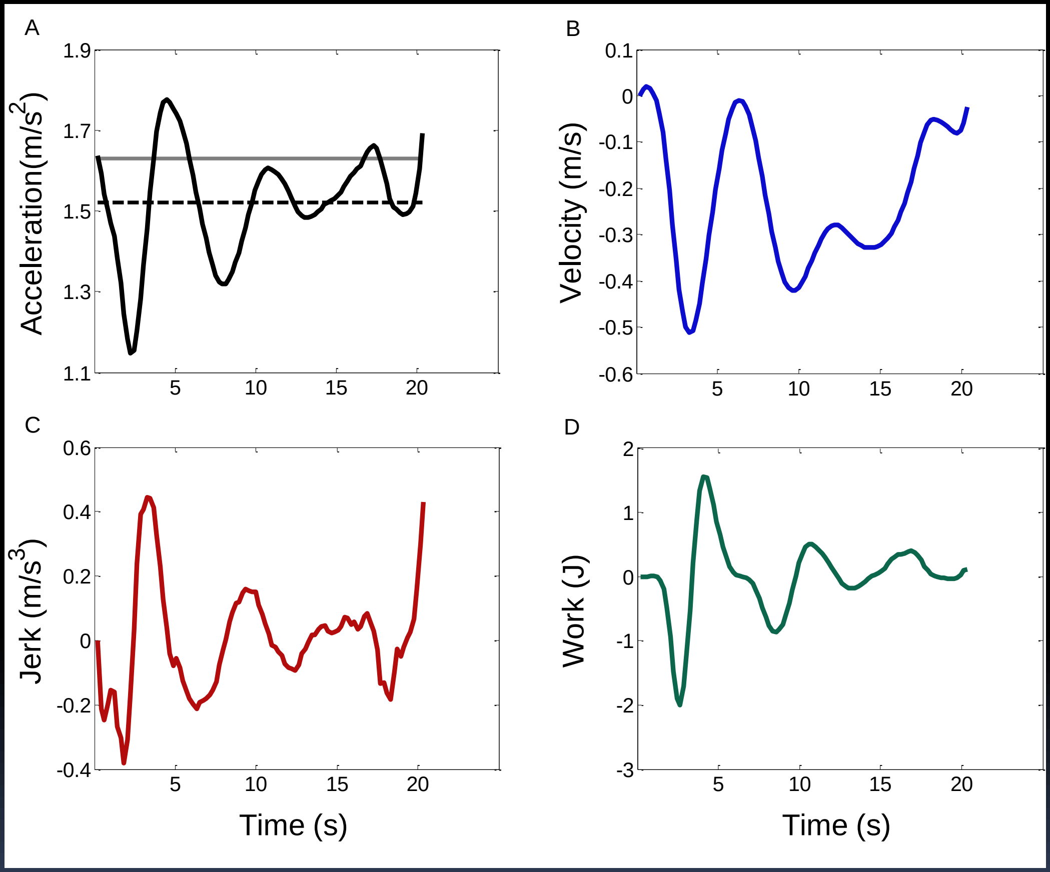
Biomechanics collection equipment



NOTE: larger capture volume than Phase I; still not long enough walkway for subjects to attain stable gait pattern through capture volume

C-9 Accelerations

Sample Parabola



- Resultant force from *g* level changes
- Change ≥ over 30% of average male's bodyweight at 1/6 *g*
- Creates problems for control & stability (walking, balance)
- C-9 walk speed ≈ 0.7 m·s^{-1}
- Work to walk ≈ 1.85 ± 0.57 J·kg^{-1}·m^{-1}
  - *AE Minetti et al. J Appl Physiol 93: 1039–1046, (2002)*

(A) Acceleration of a sample parabola (black) with the parabola mean acceleration (dash) and 1/6th Earth gravity (gray)
(B) Velocity (B), jerk (C) and work (D) as calculated from the original acceleration data
(C) The mass used for the work calculation was 80 kg

C-9 Accelerations

Over-all Parabola Statistics

	Mean	St Dev	Max	Min
Velocity (m/s)	0.34	0.56	10.4	-6.8
$\bar{x}$ Acceleration (m/s^2)	1.6	0.14	1.8	1.4
Δ Acceleration (m/s^2)			0.7	-0.54
Jerk (m/s^3)	-0.02	0.11	0.44	-0.8

Data is from 219 parabolas
Missing 1 day of parabola data

Example of EVA Human Performance Testing during Parabolic Flight

Mass/Weight/Gravity Test Design (C-9)

∆ Weight (Simulated Mass) Testing

- Constant Factors
  - Mass*
  - CG*
  - Moment of inertia*
- Varied Factors
  - Gravity

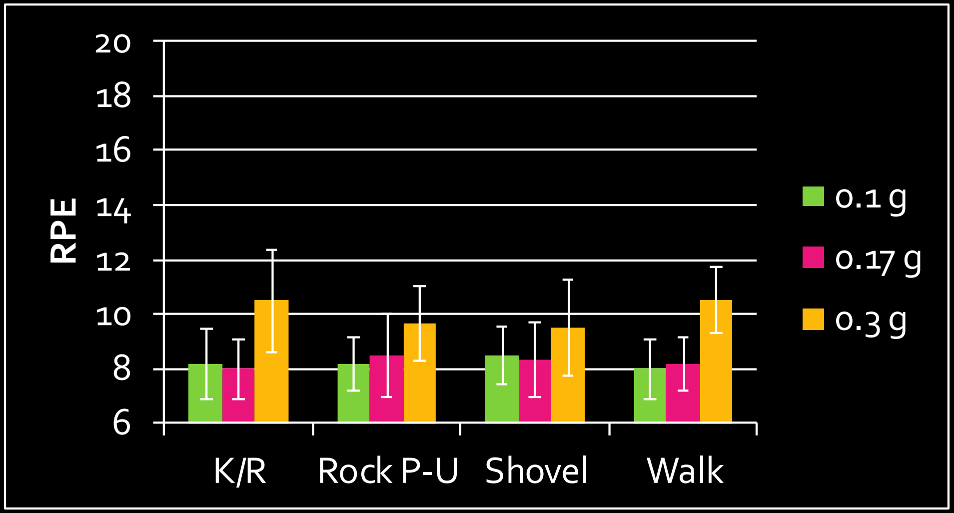
∆ Mass Testing

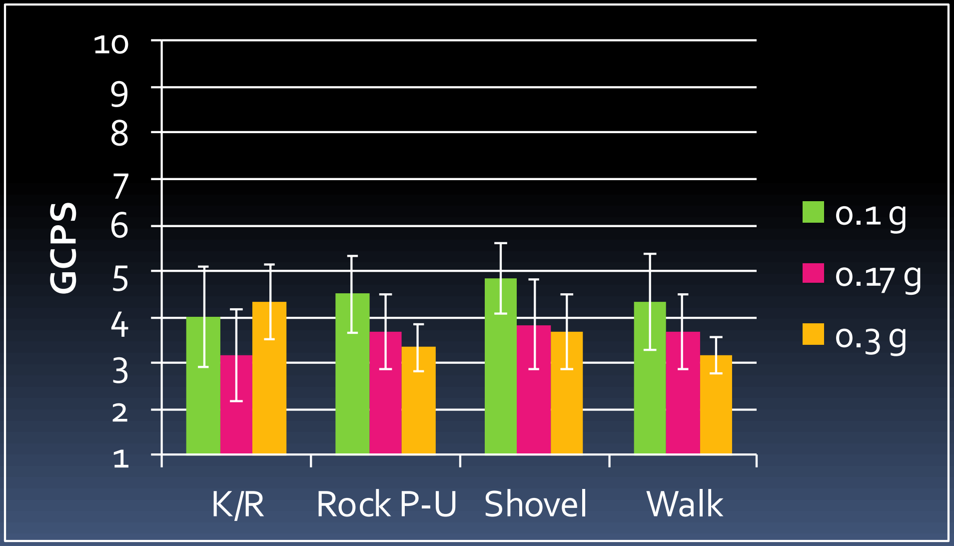
- Constant Factors
  - Gravity
  - CG*
- Varied Factors
  - Mass
- Ignored Factors
  - Moment of inertia

* These factors can vary between subjects, especially as they drift from the reference subject (6', 180 lb)
- 5 subjects were constant across all of these test points

∆ Weight (Simulated Mass) Results (C-9)

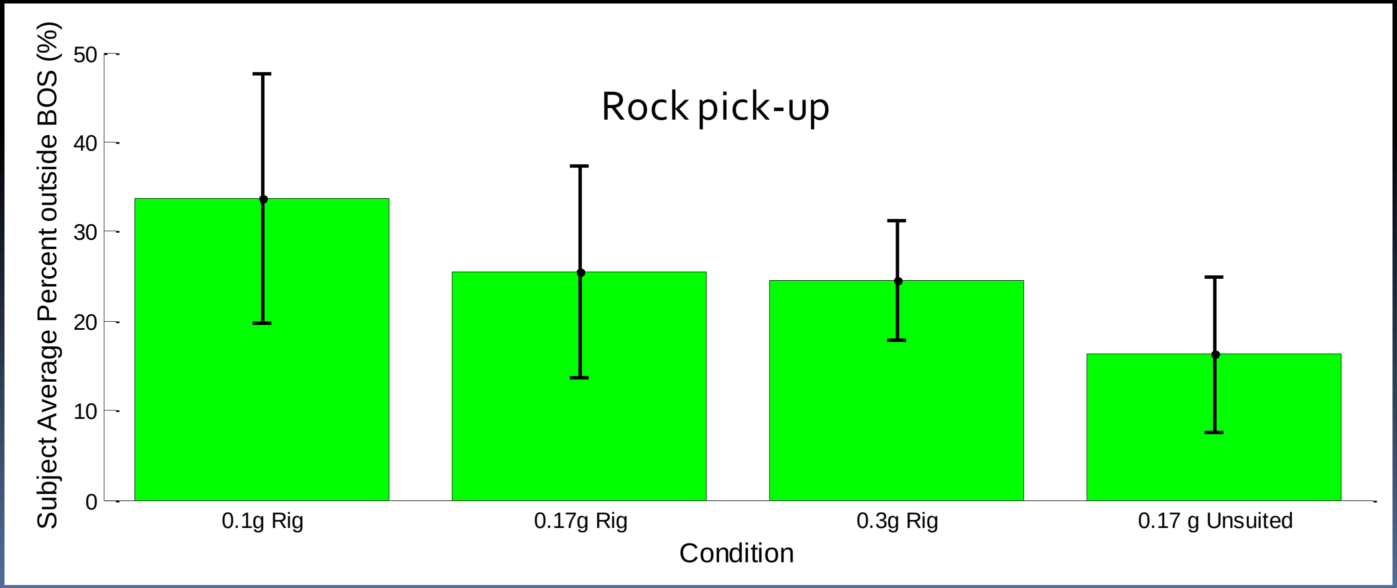
- RPE ↑ for all tasks with ↑ gravity
  - Perceived effort level was light/fairly light for all tasks
- GCPS ↓ for all tasks except kneel/recover with ↑ gravity
  - GCPS values of 3-5 border on acceptable performance, but indicate improvements warranted





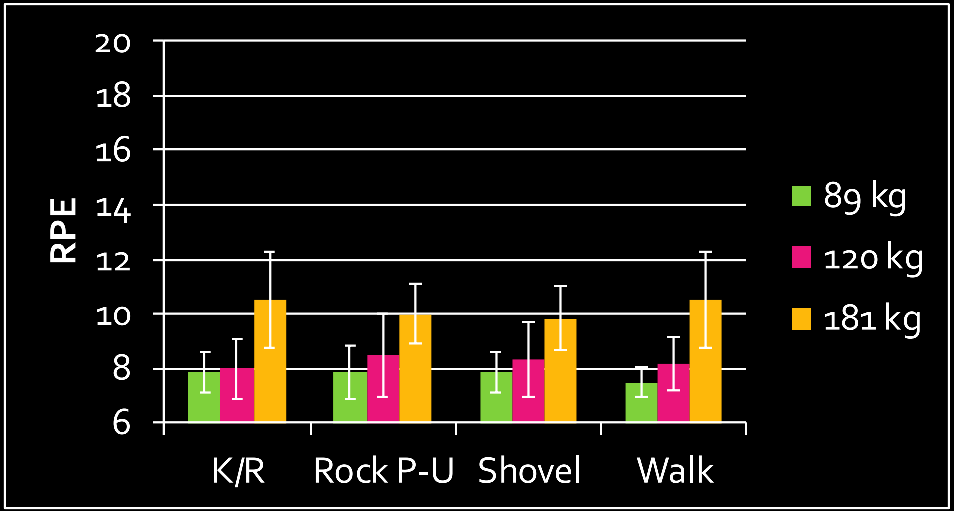
Δ Weight (Simulated Mass) Results (C-9)

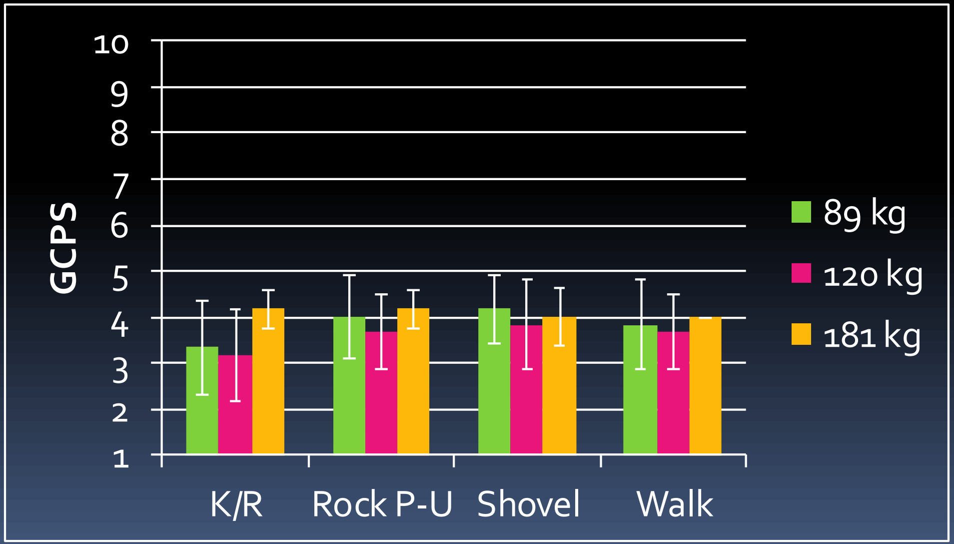
- Ambulation
  - No conclusive evidence from Phase I flights that supports kinematic or kinetic changes with changes in gravity level
  - No evidence to elucidate the influence that gravity and rotational inertia play on subject dynamics
- Exploration
  - Example: rock pick-up when suited, as gravity increased, percent of time outside base of support decreased



Δ Mass Results (C-9)

- RPE ↑ for all tasks with ↑ mass
  - Perceived effort level was light/fairly light for all tasks
- GCPS results mixed
  - GCPS lowest with 120 kg mass but with large amount of variability
  - GCPS values of 3-5 border on acceptable performance, but indicate improvements warranted





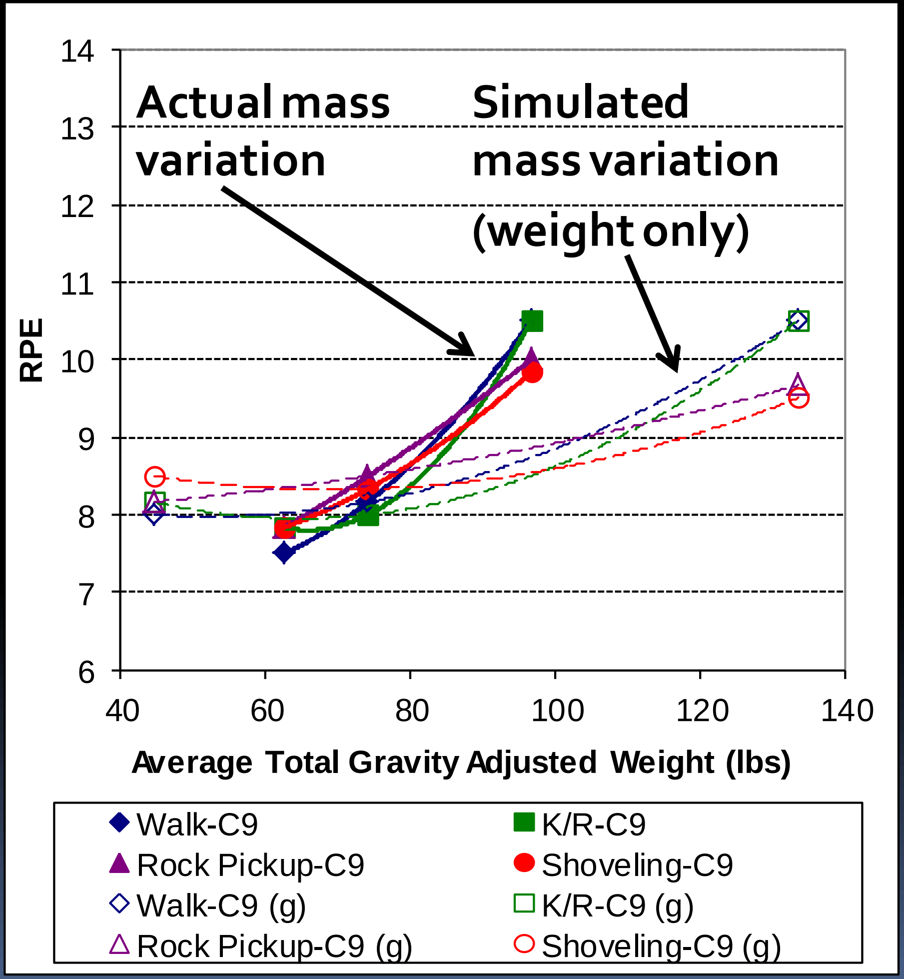
Δ Weight vs. Δ Mass Testing (C-9)

	Subject Mass (kg)	Suit/CG Rig Mass (kg)	Gravity Level	TGAW
Δ Weight (Simulated Mass) Series	80	120	**0.1**	196 N (44 lb)
	80	120	**0.17**	333 N (75 lb)
	80	120	**0.3**	588 N (132 lb)
Δ Mass Series	80	89	0.17	282 N (63 lb)
	80	120	0.17	333 N (75 lb)
	80	181	0.17	435 N (98 lb)

- How well does changing weight (offload) represent the human performance changes seen with actual changes in suit/system mass?

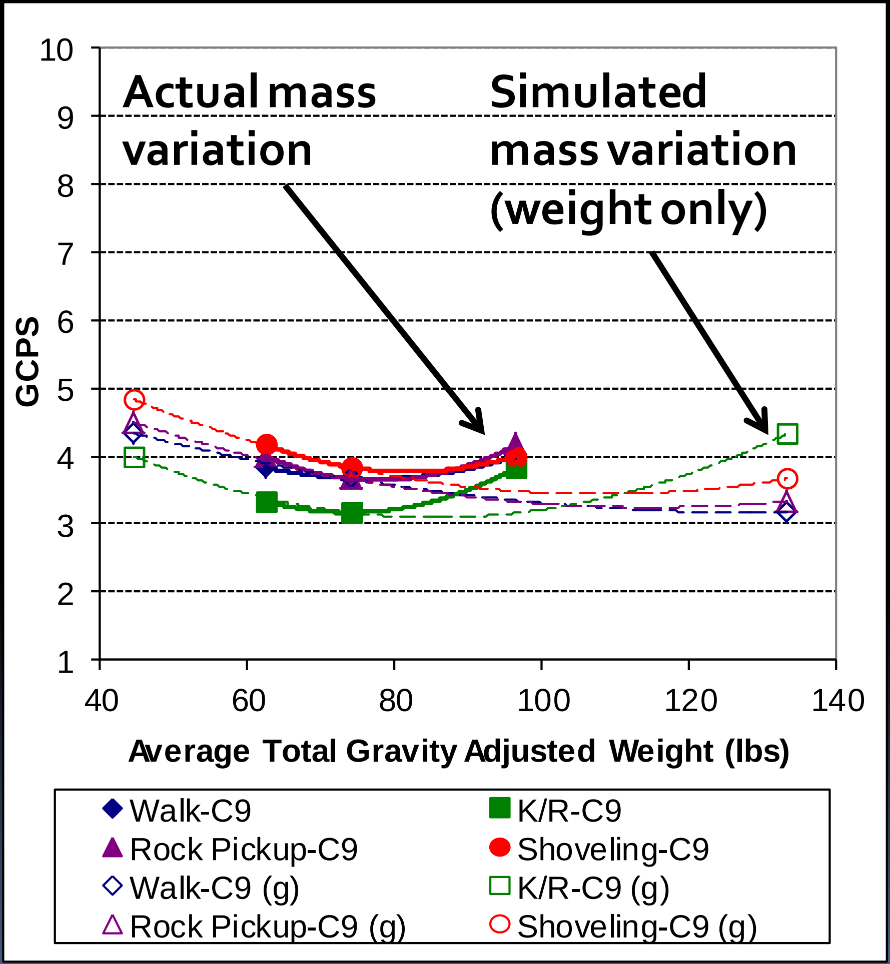
Δ Weight vs. Δ Mass Results (C-9)

- RPE results indicate that simulating mass by changing weight alone does not accurately reflect the RPE changes seen with an increase in actual mass
  - Trends more similar when simulating lower masses
  - Simulating small mass changes (5-10 lb TGAW) may not affect RPE significantly



Δ Weight vs. Δ Mass Results (C-9)

- GCPS results indicate that simulating mass by changing weight alone does not accurately reflect the GCPS changes seen with an increase in actual mass
  - Trends are quite similar when simulating lower masses
  - Simulating small mass changes (5-10 lb TGAW) may not affect GCPS notably



Unsuited Δ Weight & Δ Mass Results (POGO)

Unsuited Condition	Average TGAW (lb)	Busy Board (l/task)	Rock Transfer (l/task)	Shoveling (ml/kg rock)
1 *g* Baseline	180	0.87 ± 0.22	1.32 ± 0.37	24.19 ± 8.19
0.17 *g* Shirt Sleeve Baseline	30	0.83 ± 0.32	2.14 ± 0.36	28.53 ± 13.88
0.12 *g* Weight-Matched	53	0.82 ± 0.26	2.17 ± 0.60	23.49 ± 8.17
0.17 *g* Weight-Matched	76	0.90 ± 0.22	2.27 ± 0.30	22.78 ± 6.37
+ 11.3 kg added mass	76	0.96 ± 0.59	2.10 ± 0.44	26.11 ± 11.59
+ 22.7 kg added mass	76	0.84 ± 0.28	2.03 ± 0.34	26.64 ± 9.61
+ 34.1 kg added mass	76	0.80 ± 0.21	2.20 ± 0.33	26.88 ± 9.51
0.22 *g* Weight-Matched	98	0.92 ± 0.32	2.17 ± 0.42	23.88 ± 7.55

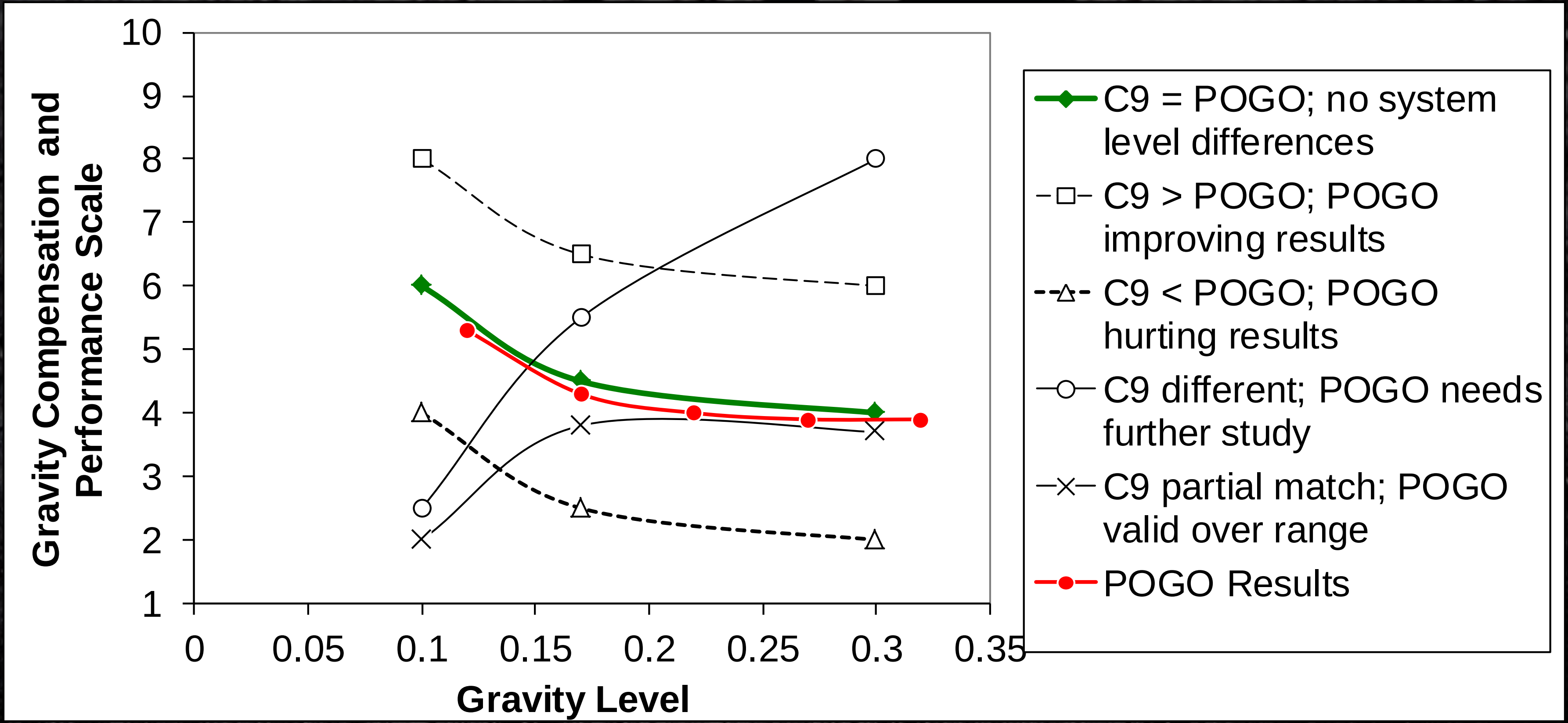
1. Little difference between conditions
2. Suggest that that with unrestricted movement, changing weight and/or mass may have little effect on perceived performance
3. POGO and/or harnessing methods may have masked any significant differences
4. This was not the case during ambulation

Mass / Weight / Gravity Summary

- Human performance can be significantly affected by a change in gravity
  - Task dependent – tasks requiring greater energy expenditure are affected more (e.g., running shows greater differences than walking)
- Simulating a change in suit mass by manipulating offload does not lead to the same human performance changes as actually changing the mass
  - Simulating mass by altering weight underestimates human performance metrics at heavier masses
    - Expected outcome as subjects have the increased GRF but not the additional mass to control
  - Simulating mass by altering weight overestimates human performance metrics at lower masses
    - Expected outcome as subjects have decreased GRF with additional mass to control

Direct Comparison Possibilities

- Exact tasks can sometimes, but not always, be replicated across environments
- Data from some variables can be collected across analog environments



C-9 vs. POGO Study Design

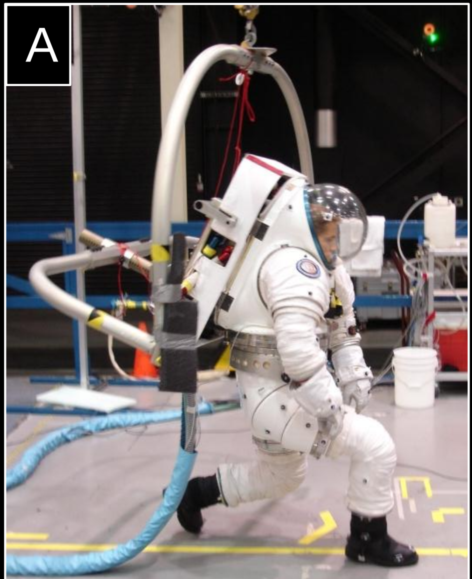
POGO Test Conditions

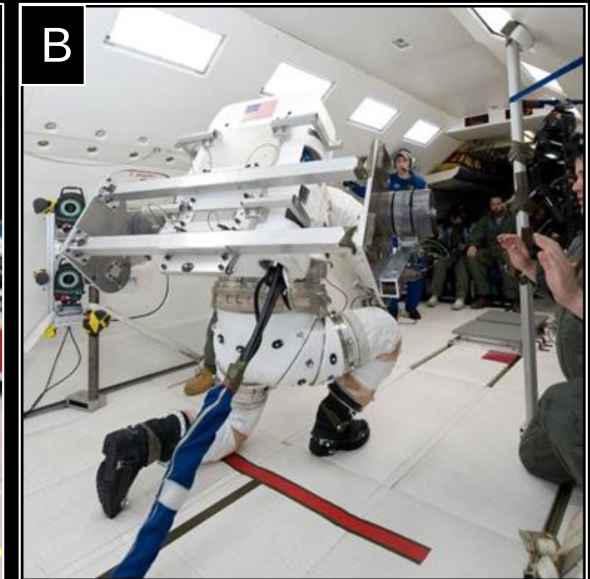
- Suit mass – 120 kg
  - Suit
  - PLSS mockup
  - Gimbal support structure
- Gravity Profiles
  - 0.12, 0.17, 0.22, 0.27 & 0.32 *g*
- Tasks Performed
  - Treadmill walking
  - Shoveling rocks
  - Kneel and recover (lunge)
  - “Rock” pick-up (2 & 12 lb lead weight)

C-9 Test Conditions

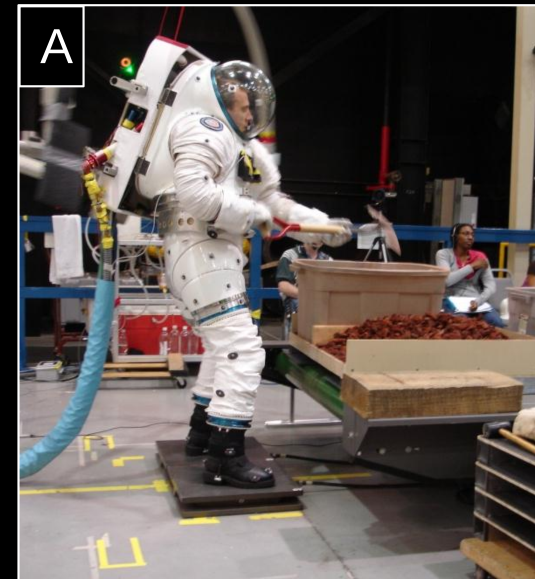
- Suit mass – 120 kg
  - Suit
  - PLSS mockup
  - CG rig - unweighted
- Gravity Profiles
  - 0.1, 0.17 & 0.3 *g*
- Tasks Performed
  - Overground walking
  - Shoveling lead shot bags
  - Kneel and recover (lunge)
  - “Rock” pick-up (6 lb lead shot bag)

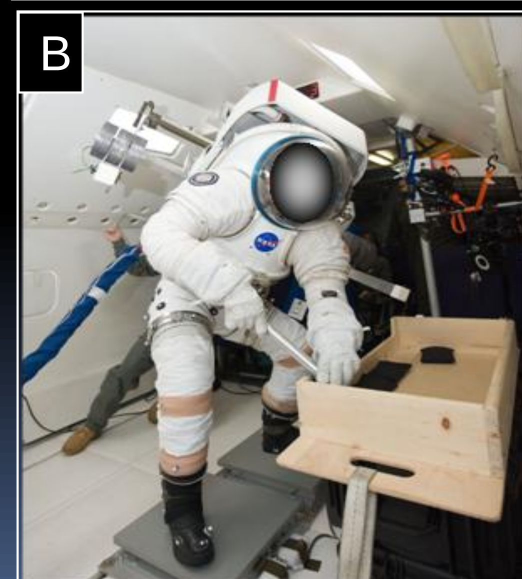
Kneel and Recover



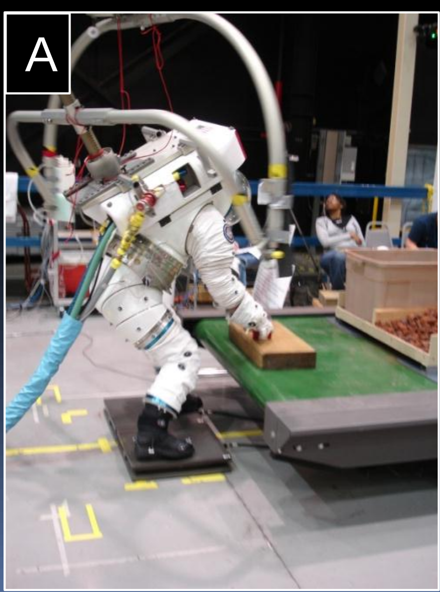


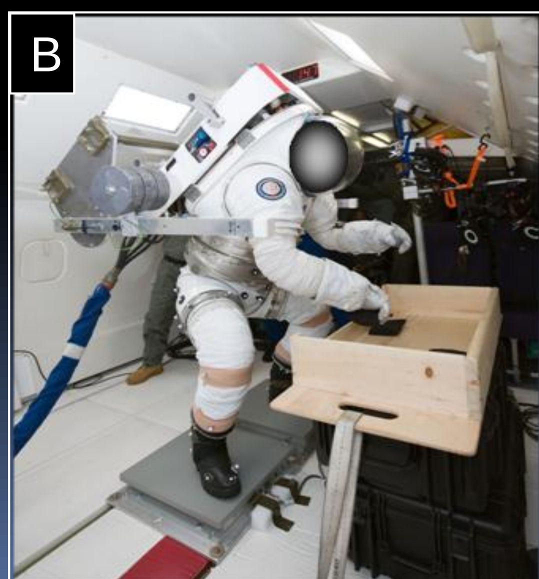
Shoveling





Weight Pickup

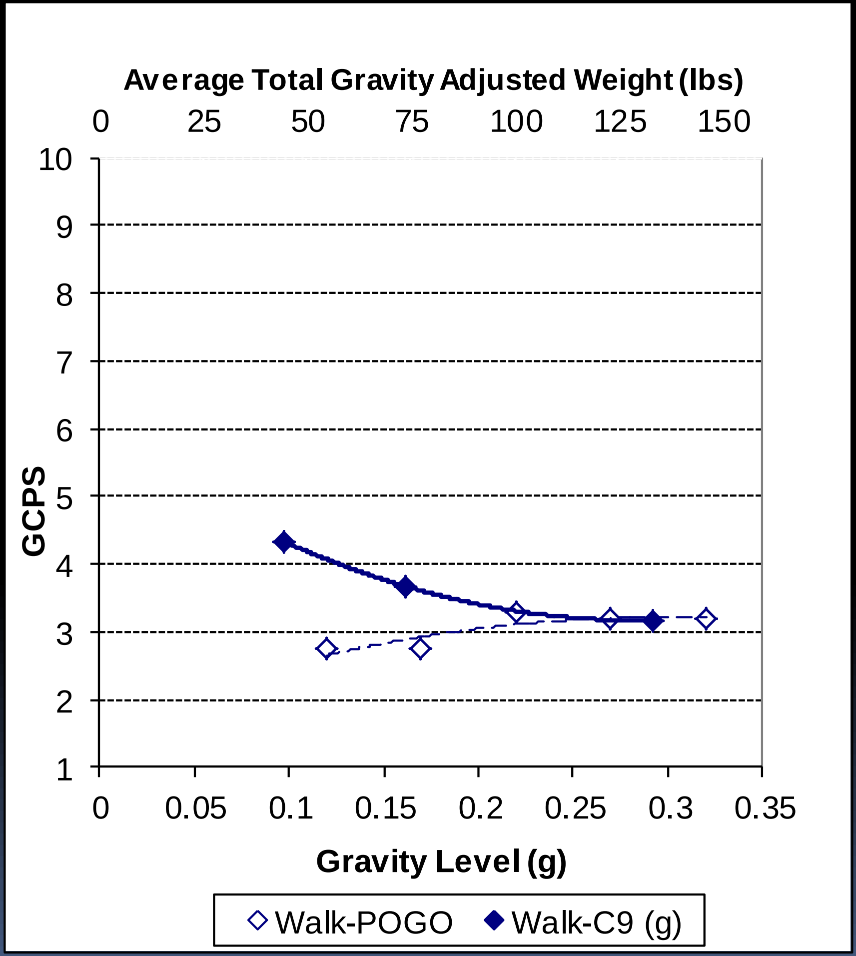




POGO/C-9 Comparison Results

- GCPS was similar at higher gravity levels
- At lunar *g* and below, the differences increased indicating system level differences
  - POGO
  - Gimbal
- Previously mentioned differences still apply

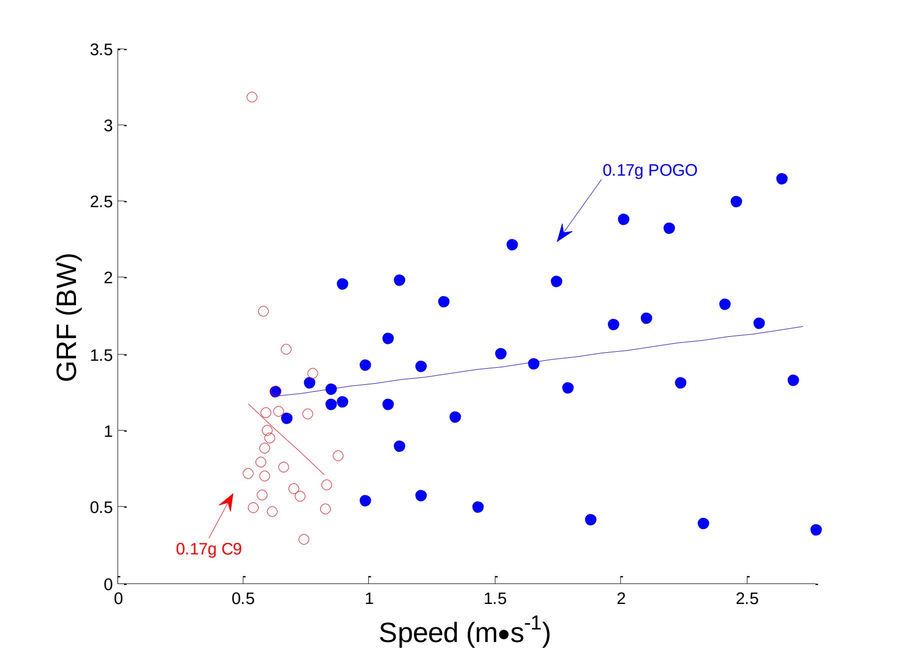
Ambulation



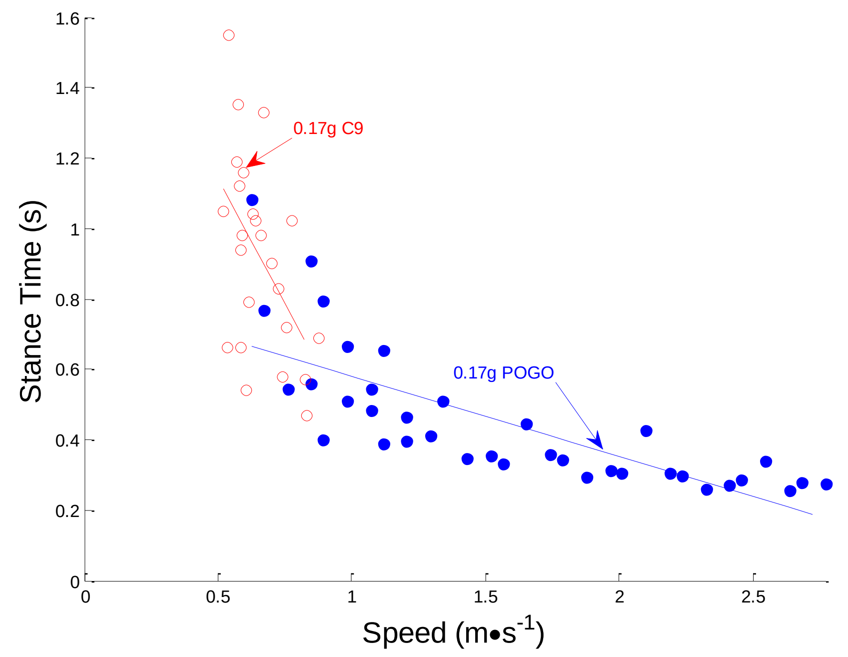
POGO/C-9 Comparison Results

Ambulation Comparison

0.17-*g*: GRF



0.17-*g*: Stance Time

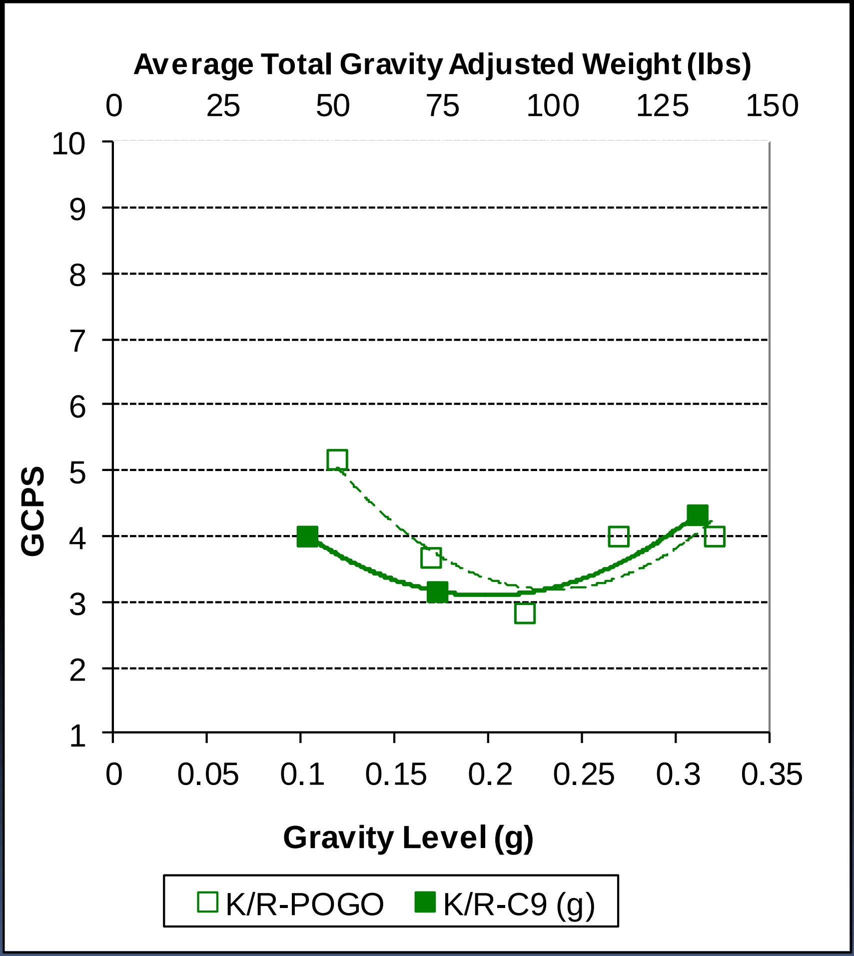


- Biomechanical data reveal two distinct system dynamics
- Different physical constraints of each test environment
  - C-9: overground walking with a short walkway
  - POGO: treadmill walking
  - Limited speed overlap hampers comparison

POGO/C-9 Comparison Results

- Most similar task between both environments
- Results are similar with biggest difference at low gravity levels

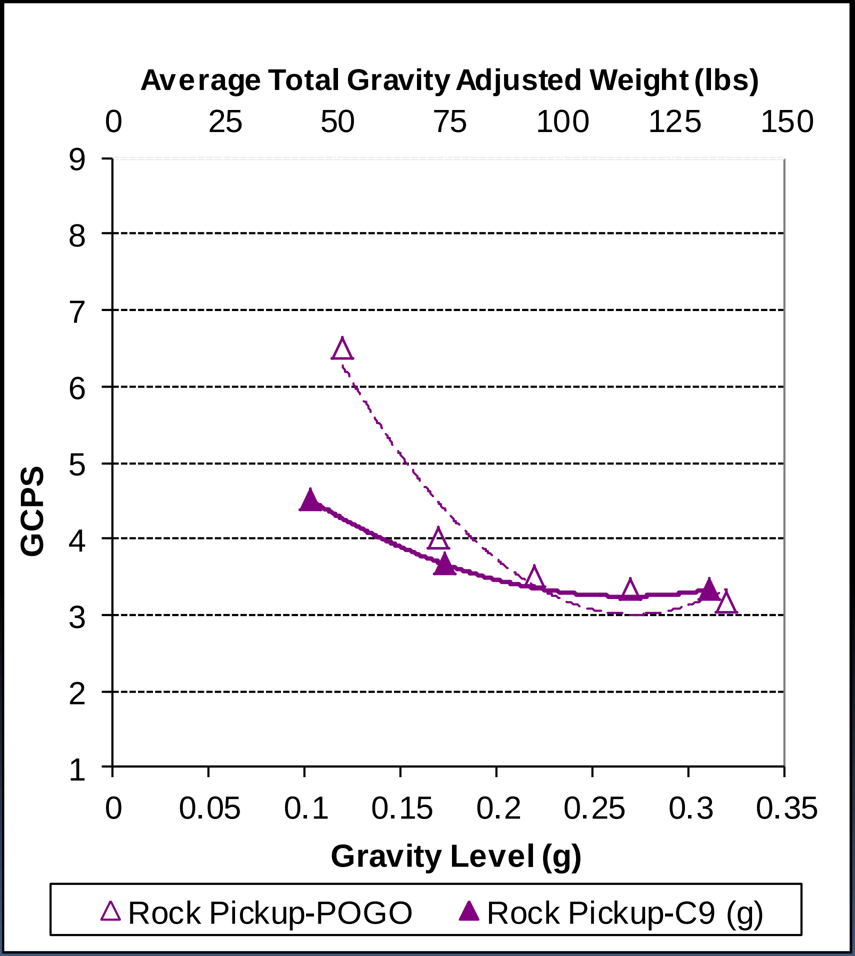
Kneel & Recover



POGO/C-9 Comparison Results

- Very similar results for lunar gravity and higher
- Big difference at lowest gravity level
  - POGO > C-9
  - Likely due to POGO gimbal interactions

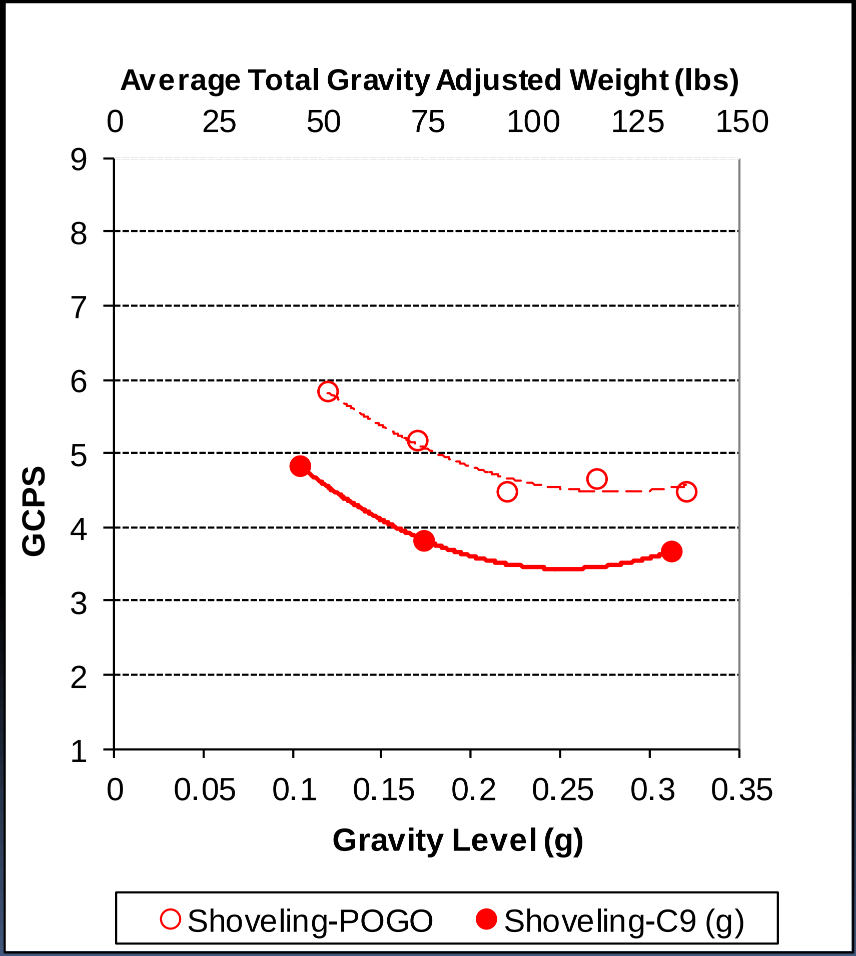
Rock Pickup



POGO/C-9 Comparison Results

- Consistent differences between POGO and C-9
  - POGO > C-9
  - Differences point to gimbal or POGO system hindering performance
- Differences between tasks limit interpretation
  - Shovels used
  - Rocks vs. bean bags

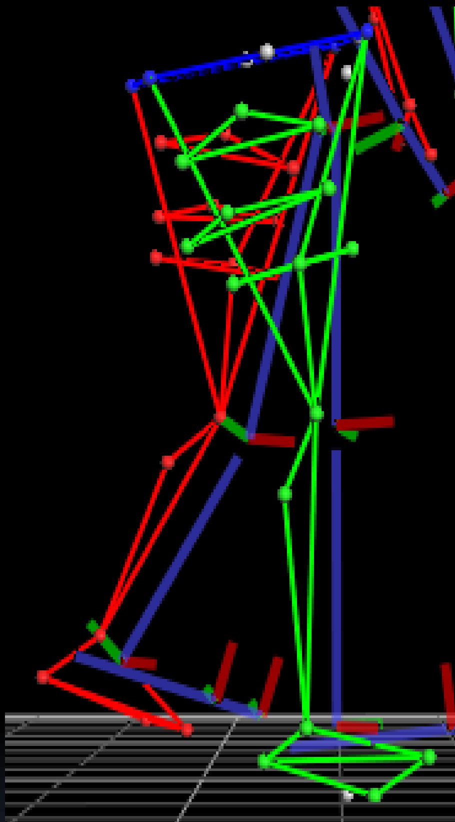
Shoveling

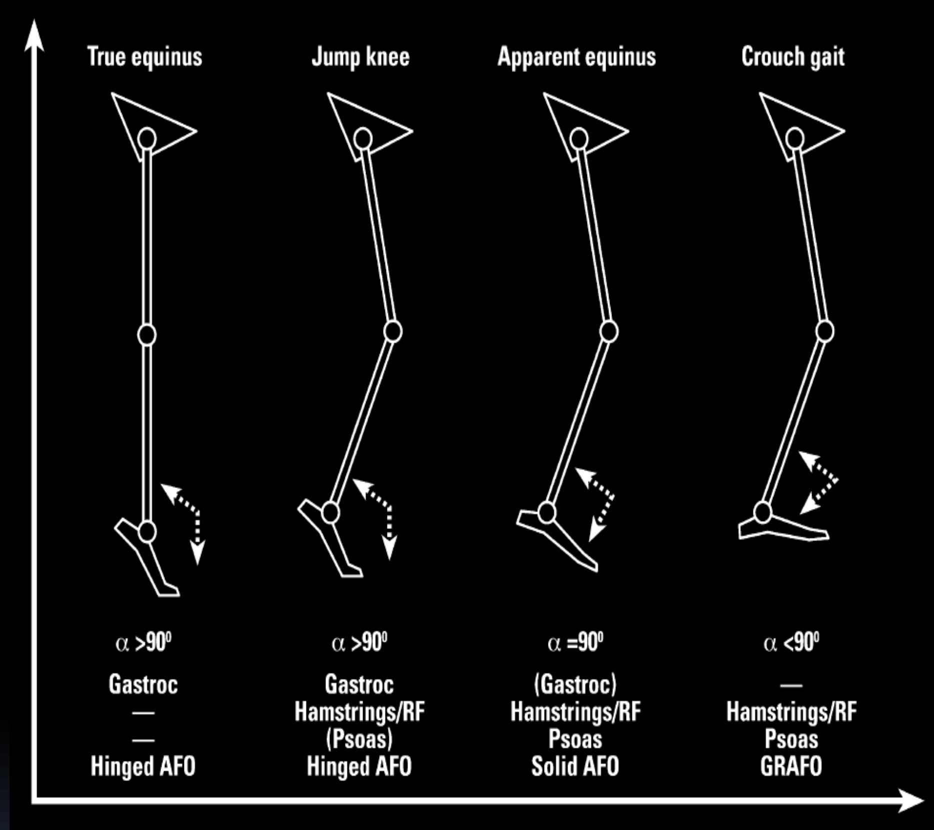


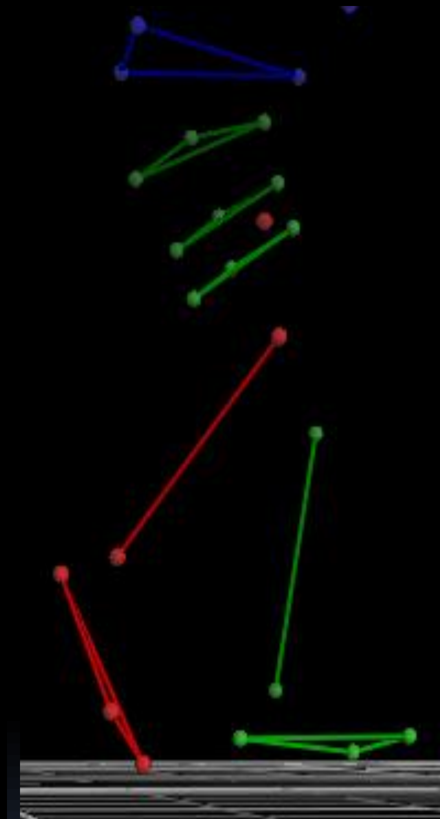
POGO Indirect Comparisons

- Many test conditions cannot be directly compared on both the C-9 and POGO
  - Concepts and trends learned from the C-9 tests can be applied to POGO results
- Data from 1 *g* unsuited conditions can be used as a first step comparison
- Literature based comparisons
  - Developing comprehensive trend analysis based on NASA studies and other research literature

POGO/C-9 Kinematic Differences





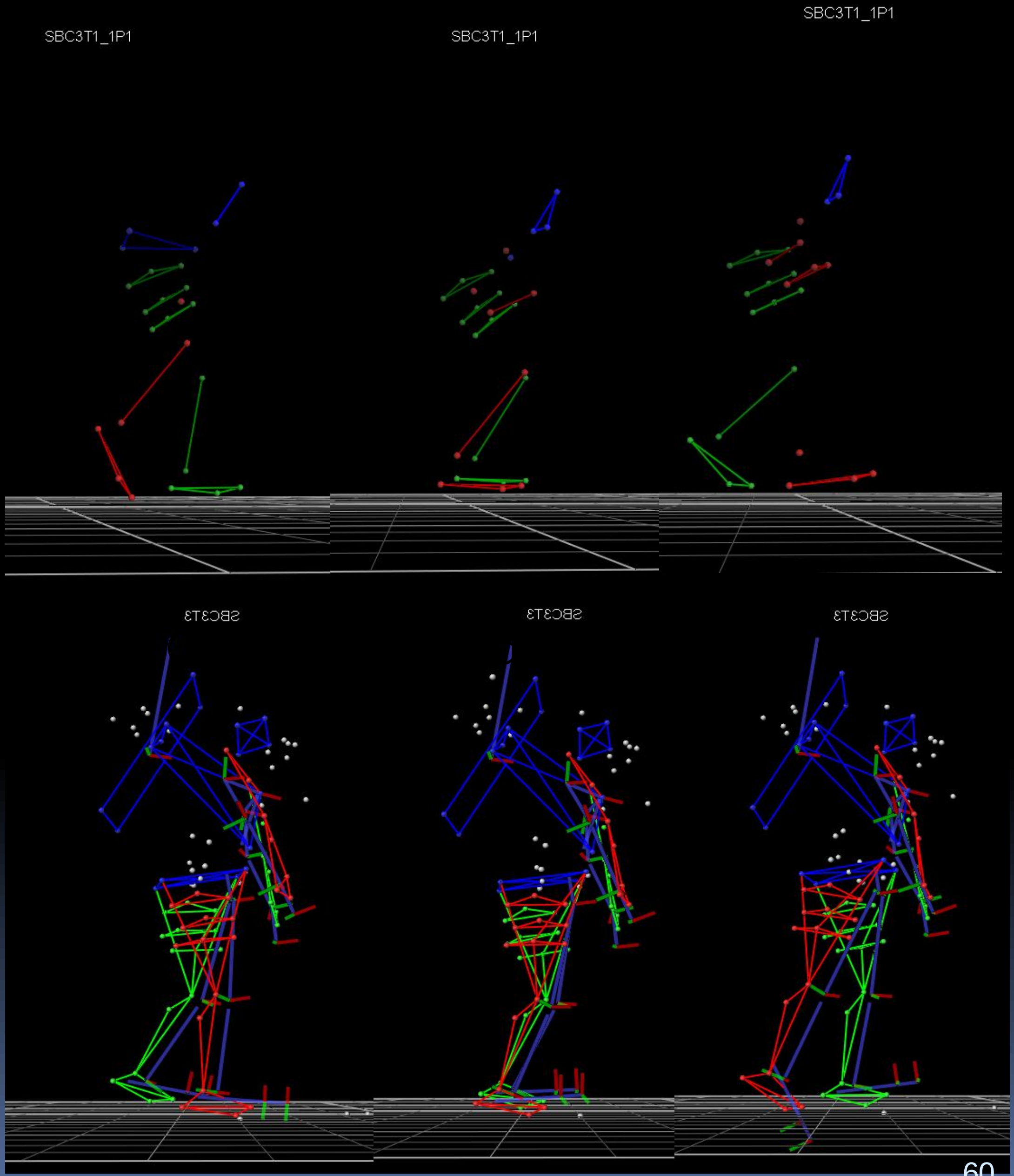


- POGO resembles “True equinus” or “Jump knee” gait patterns – very efficient, less stability, high CoM excursion (stilt walk)
- C-9 resembles “Crouch gait” pattern – less efficient, more stability, less CoM excursion

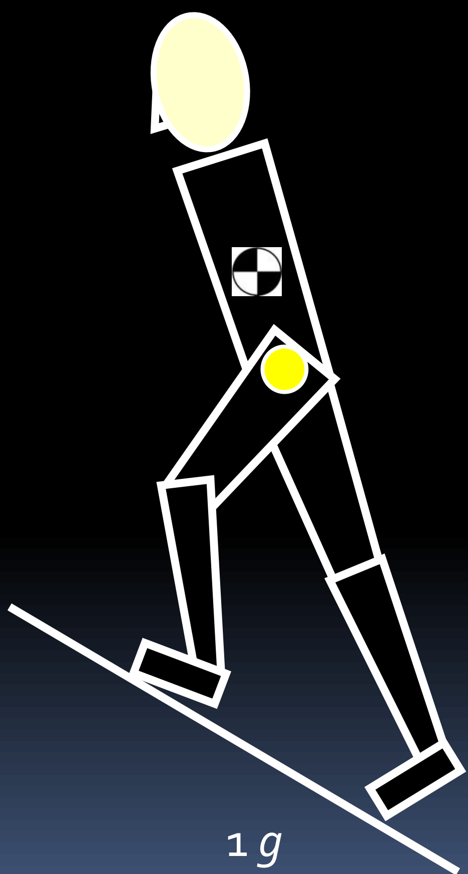
- *J Rodda, HK Graham. European Journal of Neurology 2001, 8 (Suppl. 5)*

POGO/C-9 Kinematic Differences

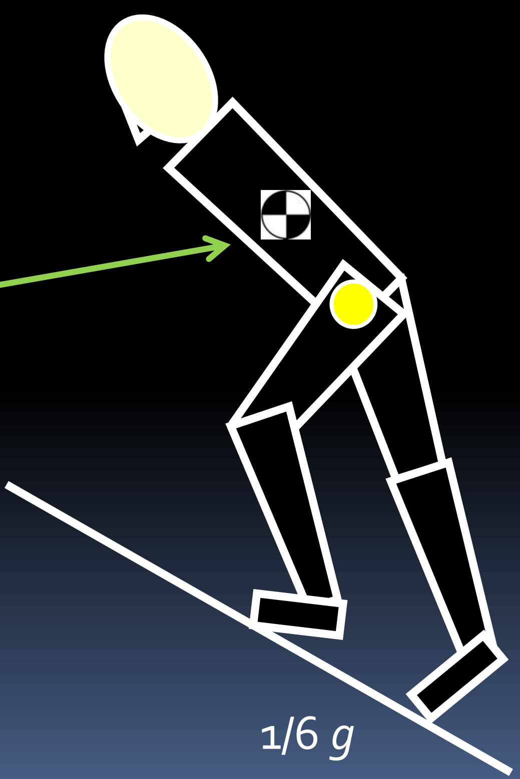
- Constant knee flexion in C-9 (crouch gait)
  - Greater hip and knee flexion in C-9
  - Greater ankle dorsiflexion in C-9
- Constant forward lean in both (same results but different causes)
- Some or near double-stance support in C-9, but complete lack of it in POGO



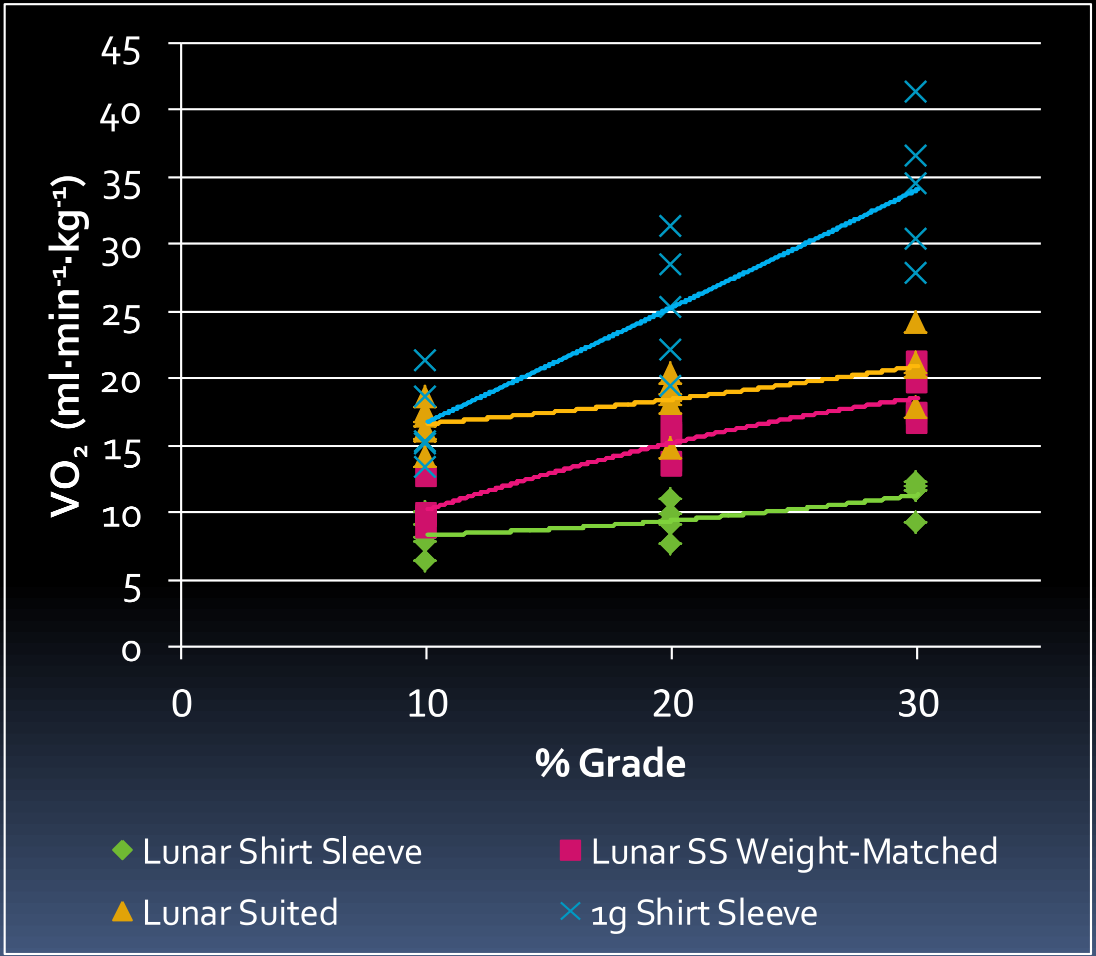
POGO Incline Walk Prediction



CoM is shifted forward even more than in 1-*g* to generate large enough forces to accomplish forward motion (due to increased CoM shift during C-9 walking in 1/6 *g*)

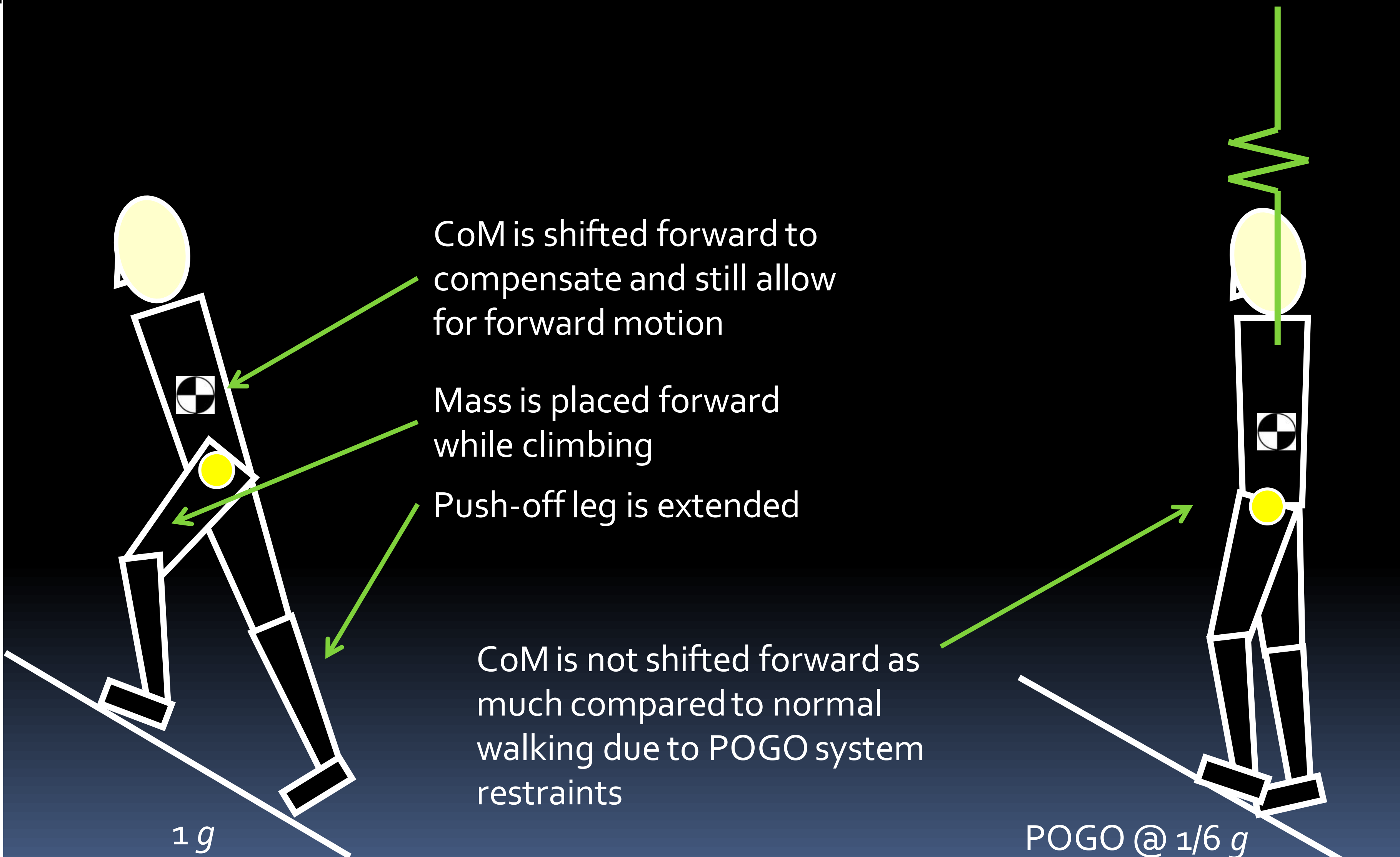


POGO Incline Walk Results

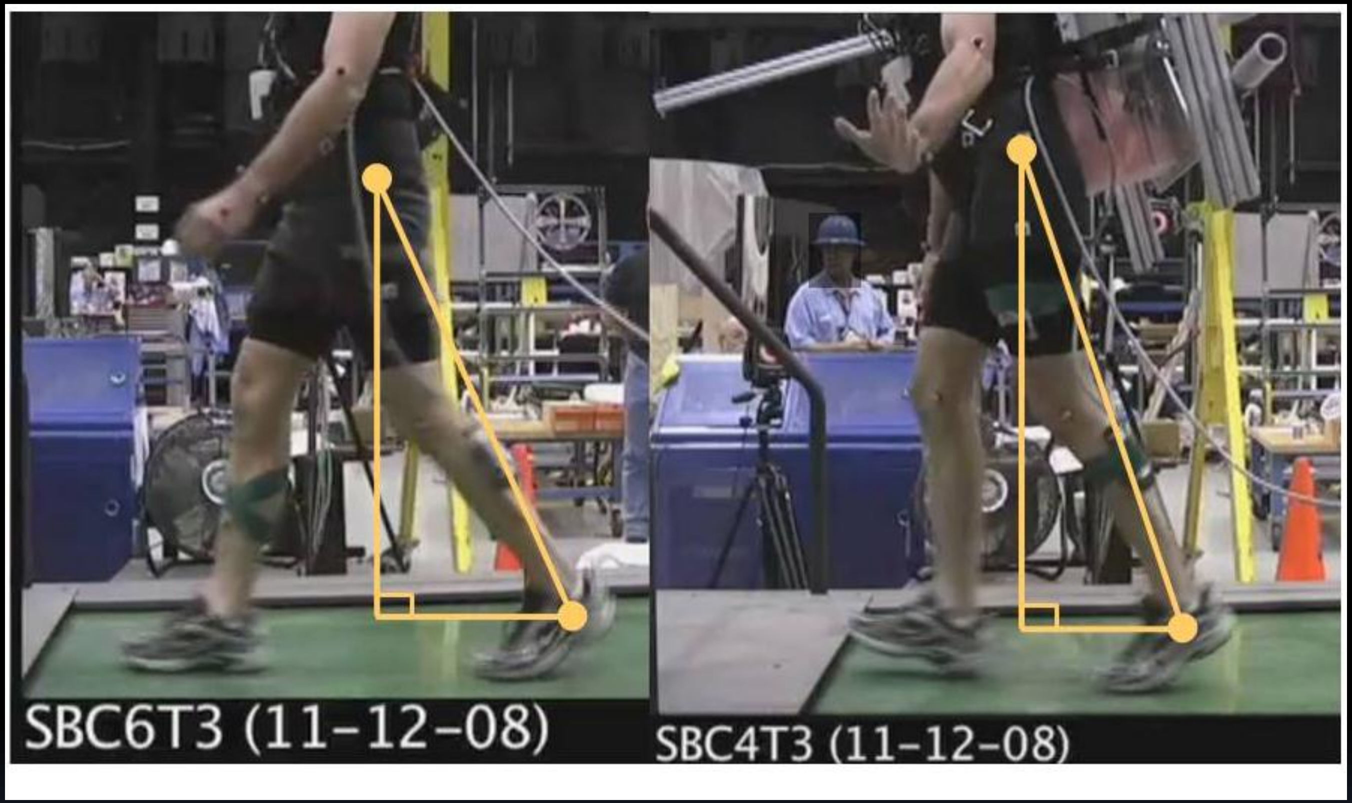


- Rate of metabolic rate increase for suited inclined ambulation was ≤ unsuited trials
- Is there an energy recovery in the system?
  - POGO
  - Suit

POGO Incline Walk Measured

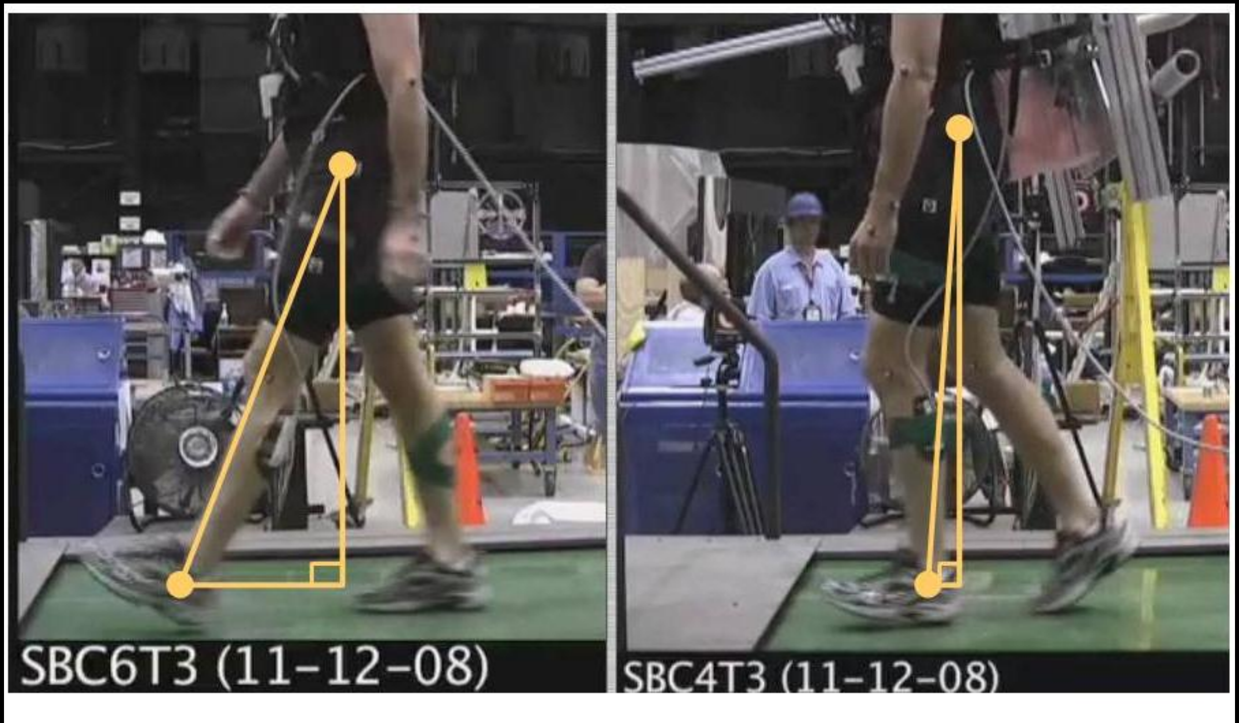


POGO Offloading Mechanics



- Changes to traditional heel strike and toe-off patterns were not observed during the CG Rig trials
- Stance phase of the gait cycle and the contact angle of the leg have been shortened so the leg can no longer **produce** as much propulsive force in the forward direction

POGO Offloading Mechanics



- Stance phase of the gait cycle & contact angle of the leg have been shortened so the leg no longer absorbs energy produced by the body's forward momentum
- Reduction of the stance phase of gait and leg angles over that contact period indicates that the body no longer imparts as much energy into the ground for propulsive means
- If the body is still imparting force into the ground to move the body CG, the mechanics of the system dictate that the body is using primarily vertical propulsive forces

POGO Analog Summary

Advantages

- Large area allows for many forms of data collection
- Long durations allow steady state tasks and metabolic assessements
- Ability to start and stop the test freely
- Flexible scheduling
- Steady state gait patterns and metered gait speeds

Limitations

- Limited translational degrees of freedom
- Large inertial mass of overhead POGO lift column affects dynamic tasks
- Lift capacity of 400-500 lb depending on day
- Offers increased stability
  - Allow s subjects to use less stable, but more efficient gait patterns on level ground
  - Results in non-practical gait patterns/posture during inclined ambulation
- POGO offloading interaction with the human subject is not fully understood or accounted for
- Limited Z-axis travel

POGO Gimbal/Harness Summary

Advantages

- Provides pitch, roll and yaw DOF vs. a harness, which restricts pitch and roll
- Gimbal supports suited testing in MKIII
- Unsuited testing possible with different harness and spreader bar assembly

Limitations

- Harnessing methods are different for suited and shirt-sleeve subjects
- Suited gimbal is limited to MKIII and EMU
- Limited alignment with different areas of the body
- Large moment of inertia in yaw axis
- Does not allow for some complex movements
  - Limits representative EVA tasks (e.g. Picking up rock off of treadmill rather than ground)

C-9 Analog Summary

Advantages

- Most realistic simulation of reduced gravity
  - Human, suit and all equipment is at reduced gravity
- Allows movement freely in all 6 DOF

Limitations

- 15-30 sec parabola duration
  - Limits types and quantity of data
    - No metabolic assessment
- Small cabin dimensions
  - Limits data collection capability
  - Limits representative EVA tasks
  - Affects gait style and performance
- Limited time for test set-up
- Almost no time for real time troubleshooting
- Inflexible flight schedule
- Variability within gravity level per parabola

Lessons Learned - Testing

- Familiarization is critical
  - Many subjects requested a few parabolas to just “get a feel” of how to move in the suit
  - 1-g run through is critical to establishing baseline data and helps with familiarization
  - Suited metabolic cost decreased 15-31% between fam and actual trial for exploration tasks
- Think about the most limiting analog first and perform the same set of tasks during ground based operations
  - We modified 3 of 4 tasks for parabolic flight
    - All of these modifications could have been predicted and accounted for in ground based testing
  - Parabolic flight is the most realistic partial-g simulation, but also volumetrically limited
- Tasks need to be performed in the most EVA similar manner but may have to be modified
  - Once improvements are made to the system, don’t stick with the old modified testing methods if they are not EVA like
  - Keep track and report on reasons for modifying any task

Lessons Learned - Subjects

- Crew subjects must continually be involved but tests must supplement with other subjects
  - Due to mission schedules, crew subjects may not be able to complete multiple studies
    - Critical for comparison across different analogs
  - Scheduling of crew subjects is complex and sometimes limited
  - Inclusion of scientists and engineers, especially those involved with EVA systems, would increase the available subject population and drastically improve scheduling flexibility
- Significant performance differences have been seen between crew subjects performing the same task in the same configuration
  - Need to characterize subject fitness, strength, anthropometry and possibly other psychological factors (e.g., military vs. civilian)

Analog Comparison

Area of Interest	POGO***	Parabolic Flight	Underwater NBL/NEEMO	Field Analogs	*ARGOS*** (TBD)*
Translational DOF	X,Z	Limited X,Y,Z	X,Y,Z	X,Y,Z	*X,Y,Z*
Offload Capacity	~ 450 lb	0-g to 2-g	0-g to 1-g	1-g	*~ 625 lb*
Task Duration	Unlimited	<30 sec	6-hr NBL and Unlimited NEEMO	Unlimited	*Unlimited*
Metabolic Rate	Yes	No	No	Yes	*Yes*
Biomechanics	Yes	Yes	No	Maybe	*Yes*
Impediments to Motion	Inertia from overhead suspension	Severe volumetric limitations	Water drag	None	*?*
Mockup Inclusion	Yes	Very Small	Yes	Yes	*Yes*
Full EVA Simulation	No	No	Yes	Yes	*Yes*

***Does not account for gimbal related issues

Items highlighted in red show the biggest problems with the analog

Integrated Suit Testing Research Plan *Concept*

1.0 Inputs to IST

- Ops & Engineering Concepts
  - Suit Designs
  - Architectures
  - Mission Objectives
  - Specific EVA Tasks
- Stakeho... Objectives
  - HR... Exploration
- Requ...

If we don't properly address the needs in step 2.0, then the system breaks down

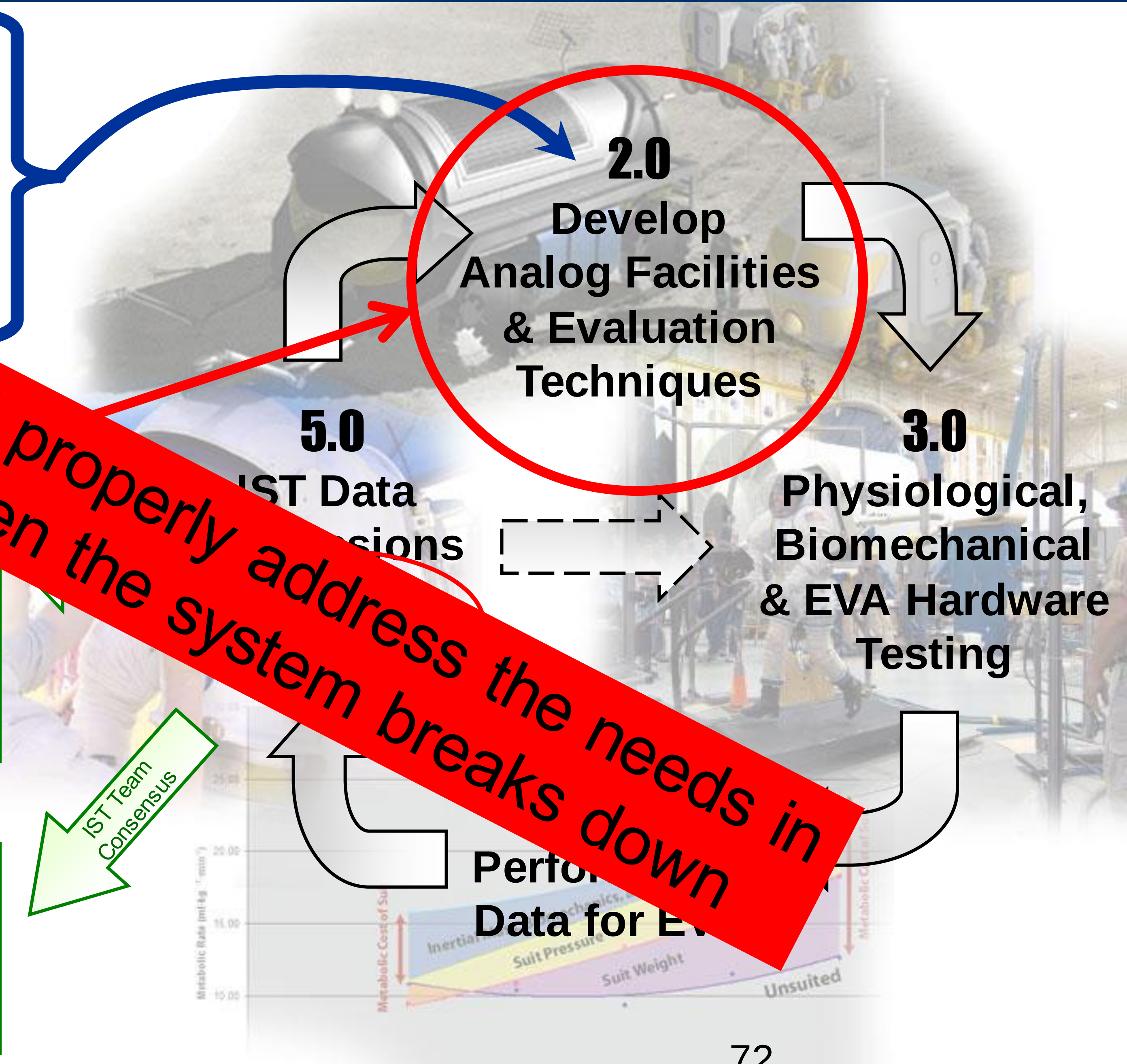
Provide inputs for requirement developme... and verification

- NASA Standard 3001
- Human Systems RB
- Exploration Analogs & Mission Development
- Other Orgs as Required

6.0

Products / Deliverables

- Test Reports / Presentations
- Model Development
- Inputs to Other Risks



ARGOS Development

Expected Improvements over POGO

- X/Y/Z translational DOF
  - Increases test flexibility with greater area available to set up tasks [1]
  - Allows subjects to move freely when doing nonlinear tasks [1]
- Active control of X/Y translational DOF
  - Eliminates inertia of POGO overhead support column [1]
  - Eliminates artificial side to side stabilization [2]
  - Eliminates artificial fore/aft stabilization [3]
- Increased lift capacity
  - Allows varied mass and CG testing
- Improved Z-axis response and accuracy

Gimbal Development

- Decreased moment of inertia
  - Less mass away from subject
  - Compact design
  - Big improvement in yaw axis
    - Example – with current gimbal, lower body movement is predominant [1]
  - Initial calculations indicate new design may have only 10-15% of the moments of inertia of current gimbal
- Decreased mass
  - Current gimbal assembly > 40 kg
  - New designs may be as low as 10 kg
- To be designed to work with other suits
- Same gimbal design will support both suited and unsuited testing

Active Response Gravity Offload System

ARGOS Videos

Active Response
Gravity Offload System
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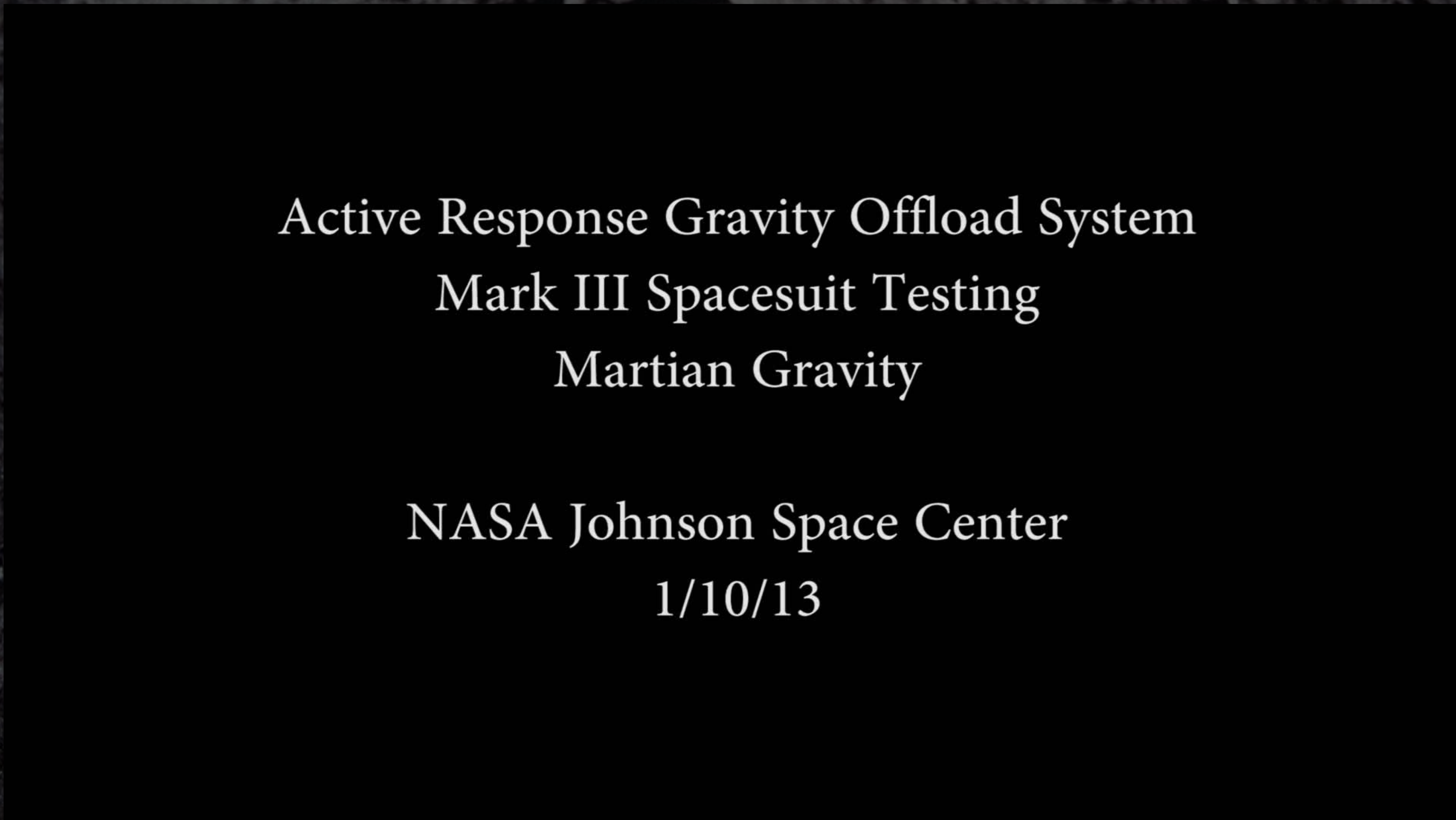
Lunar Gravity Testing

ARGOS Microgravity Simulation

ARGOS – EVA Suit Test Feasibility Testing



ARGOS
– Inclined Walking with MKIII and Z-1 in Mars Gravity

A NEW METHOD FOR INTERFACING UNSUITED SUBJECTS TO OVERHEAD SUSPENSION PARTIAL GRAVITY SIMULATORS

[1]Jason R. Norcross, [1]Steven P. Chappell, [2]Matthew S. Cowley, [2]Lauren Harvill, and [3]Michael L. Gernhardt

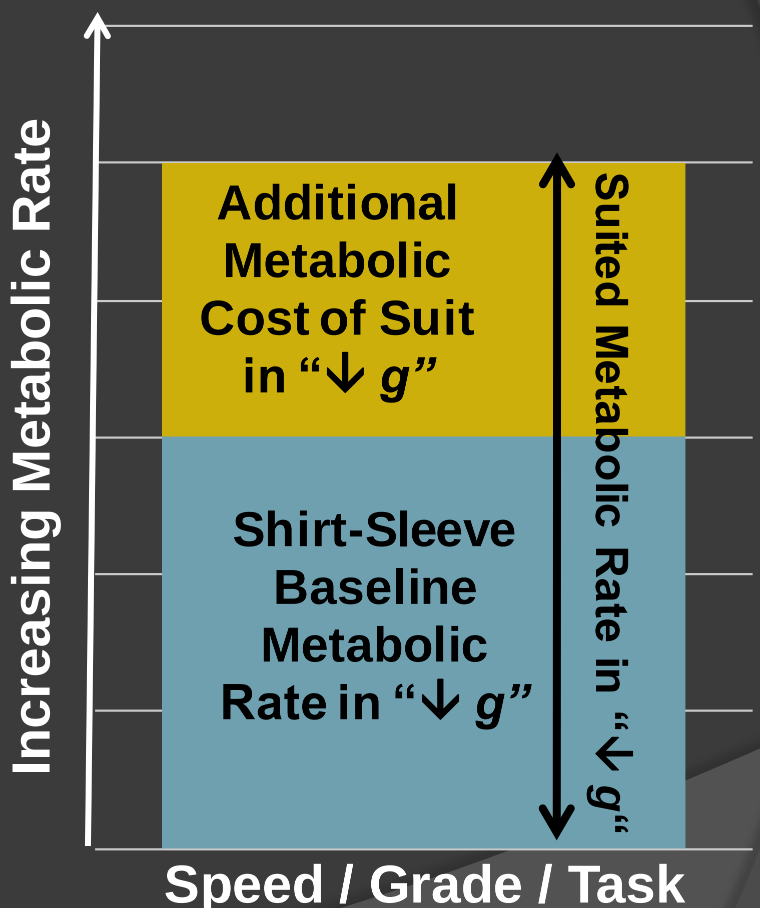
[1]Wyle Integrated Science and Engineering, Houston, TX

[2]Lockheed Martin, Houston, TX

[3]NASA Johnson Space Center, Houston, TX

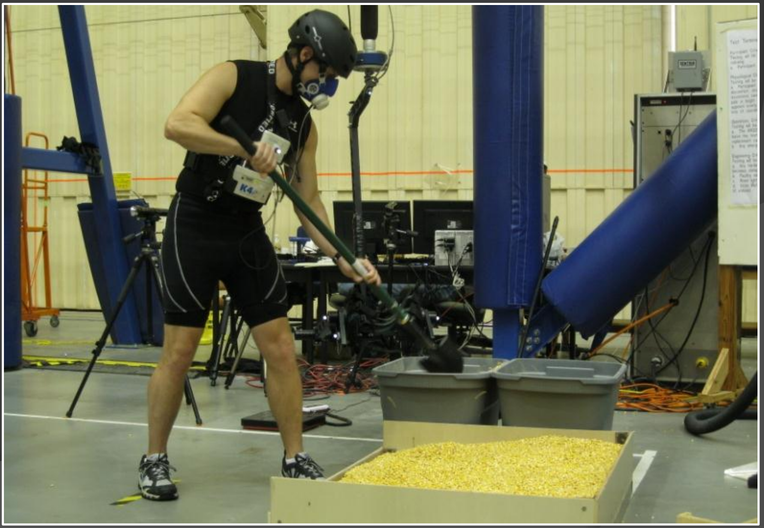
EVA Human Performance Model

- Measure 1-g shirt-sleeve performance for a target
- Characterize the baseline shirt-sleeve performance in reduced gravity
- Characterize suited performance in reduced gravity



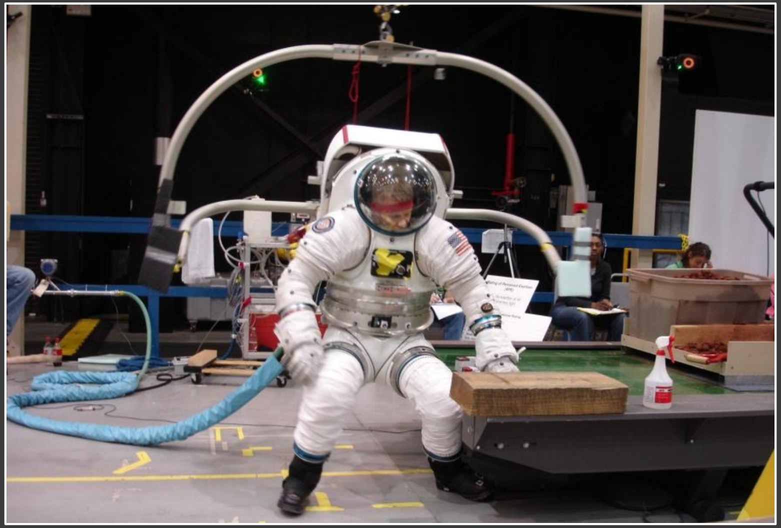
Model Requirements

- Similar shirt-sleeve and suited interface to partial gravity analog environment
  - Mobility
  - Mass
  - Mass distribution
  - CG alignment

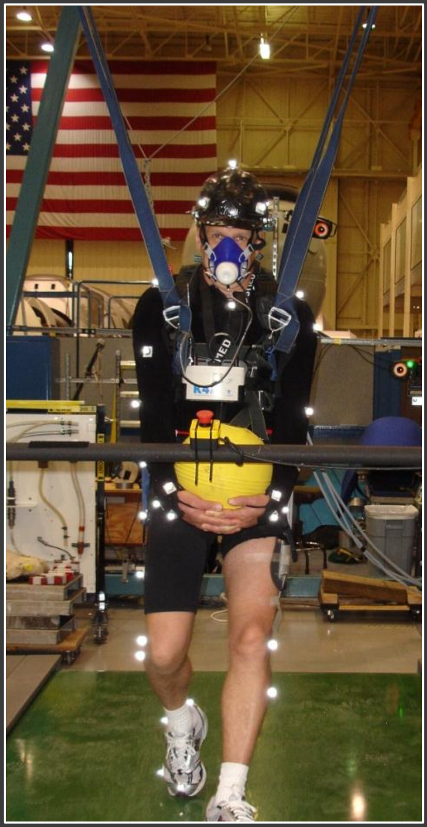


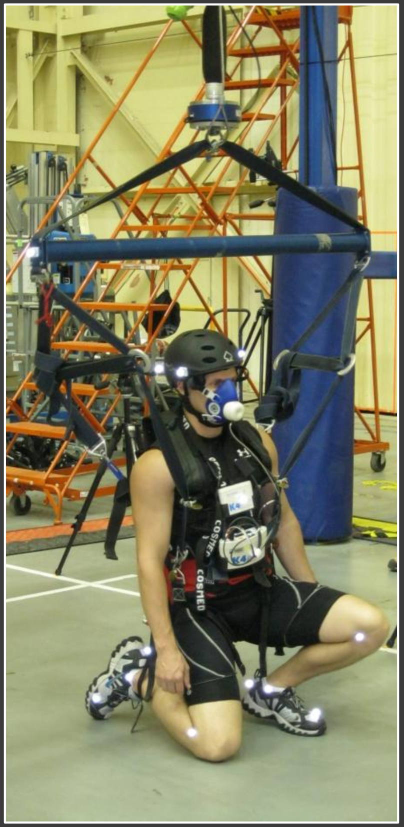
Past Interfaces

Suited Gimbal

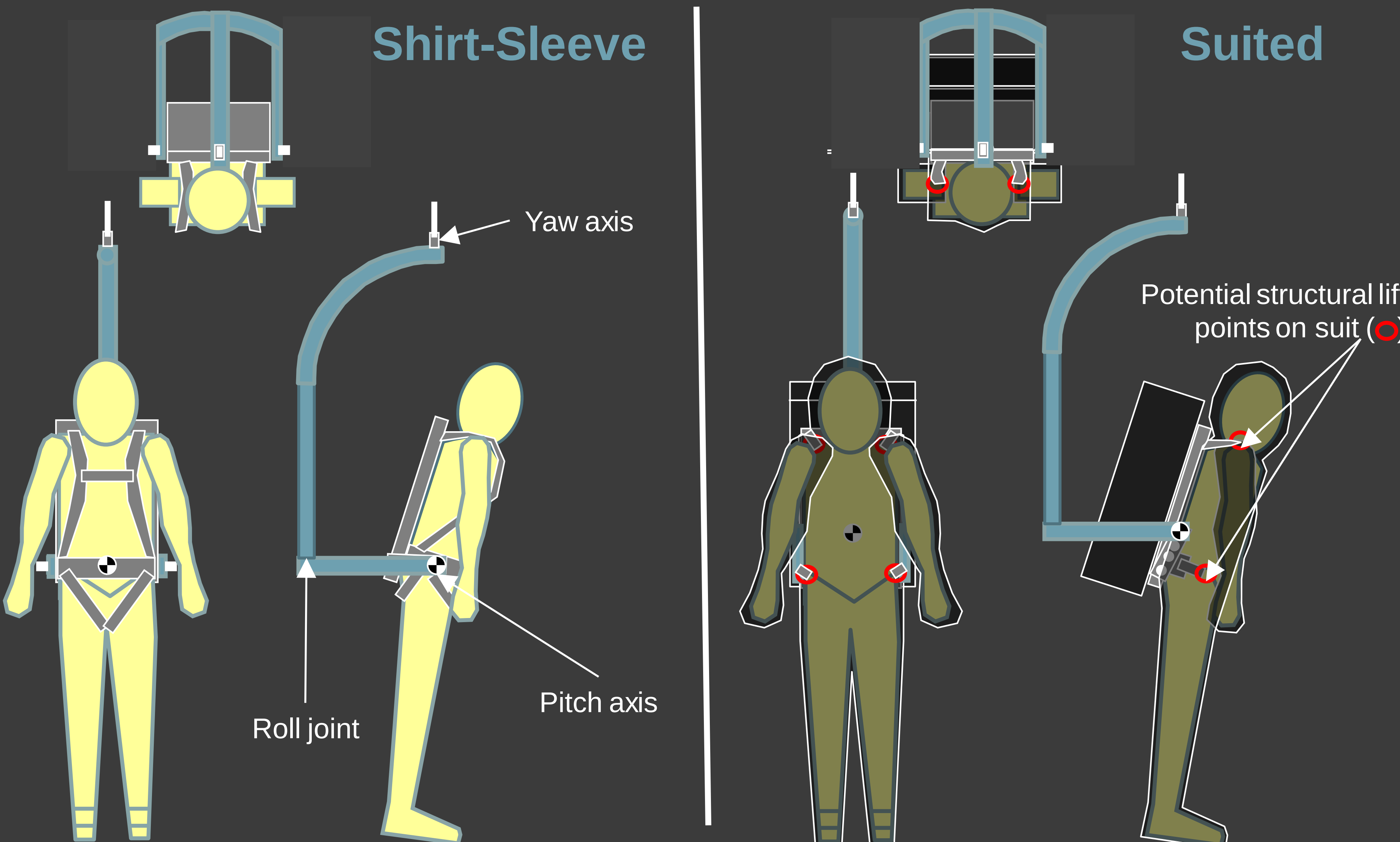


Shirt-Sleeve Spreader Bar Assembly

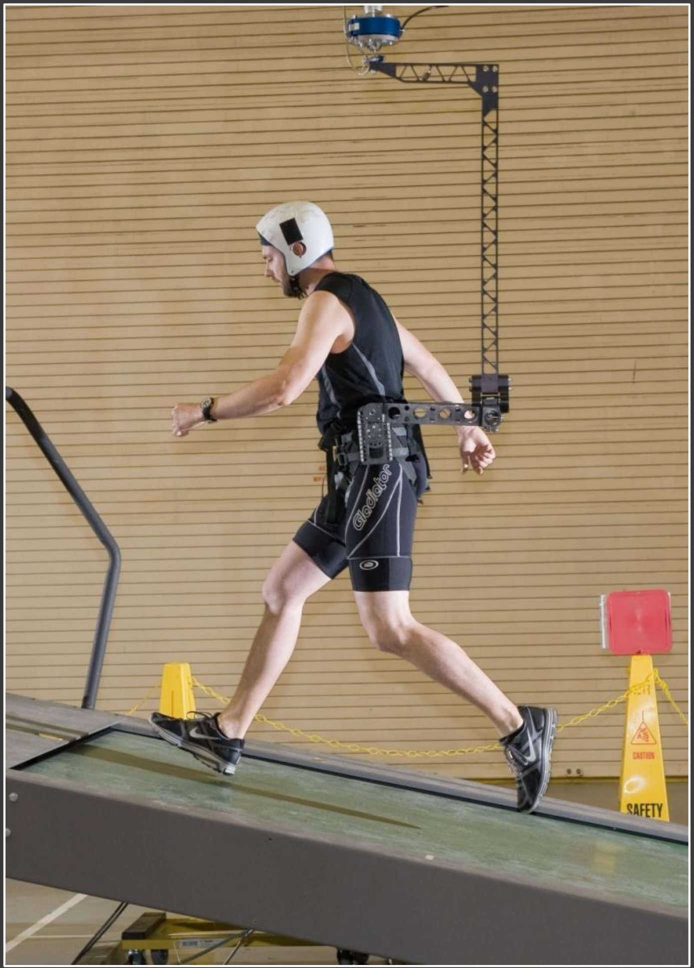


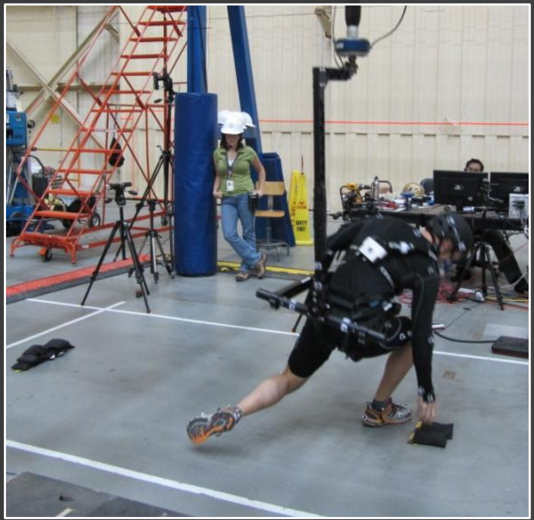


Dual Use Gimbal Concept



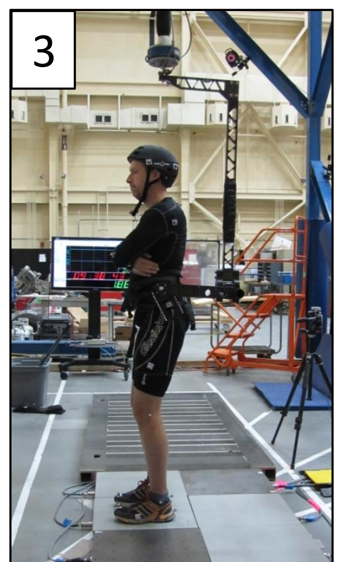
New Gimbal Concept

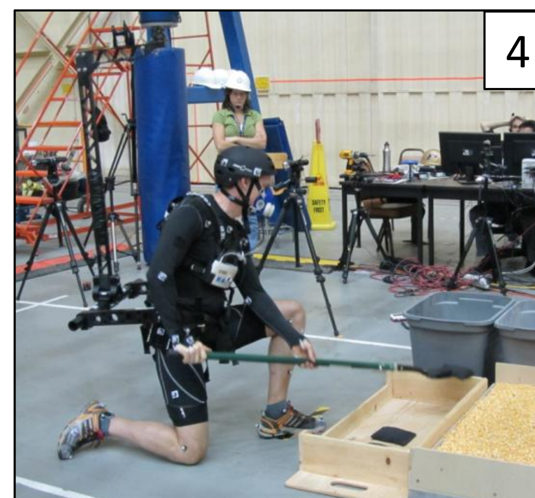




Gimbal Familiarization Session

- Before an actual test, each subject required a familiarization session that lasted 30 to 90 minutes
- The following criteria were used to evaluate for proper adjustment of the subject into the gimbal
  1. With ARGOS z-axis locked, the subject assumed a “superman” position and should be able to change direction with very subtle body movement
  2. Subject should be able to lunge down to the ground and pick up an object without leaning the trunk backward
  3. Subject should be able to stand up straight
  4. Subject should be able to use a shovel without automatically pitching forward

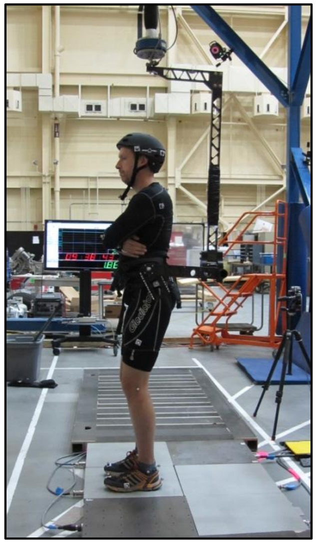




Subjects were able to complete the following tasks

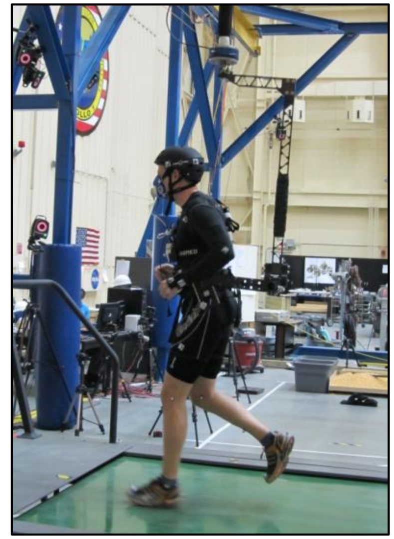
Jumping

Standing



Incline walking

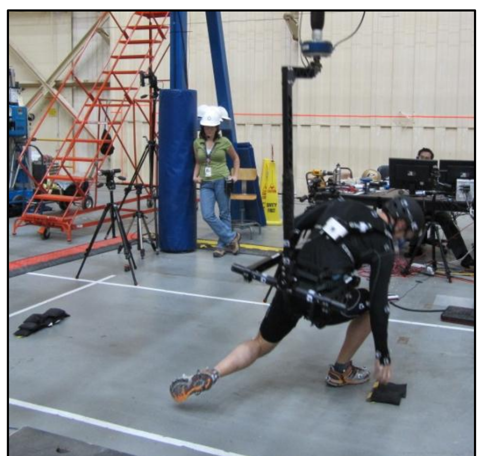
Running



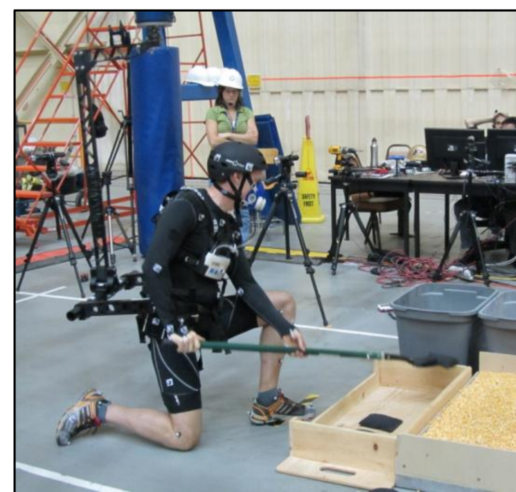
Picking up objects

Prone position and recovery

Object transfer



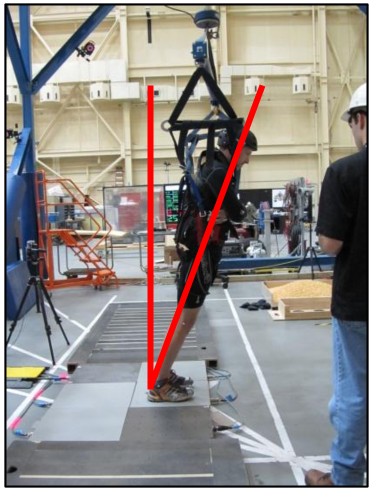
Shoveling



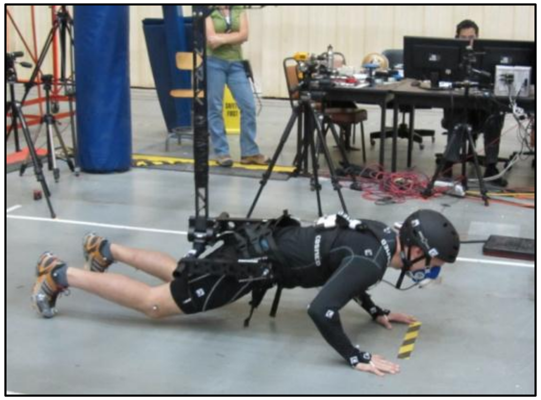
Human Factors Results Cont'd

- Functionality
  - Movement of the subject translated into movement of the gimbal or ARGOS system
    - Unlike with the spreader bar assembly, little to no energy was lost translating movement from subject to gimbal to ARGOS
    - Jump heights increased dramatically with the gimbal relative to the spreader bar
    - Subjects could fall forward in the gimbal, whereas this was not possible with the spreader bar

Terminal forward lean point in the spreader bar assembly - you could not fall if you tried



Forward lean in the gimbal past this point~~,~~ led to falling forward into the prone position



Purpose

- To evaluate human performance differences between the spreader bar assembly (SBA) and new gimbal

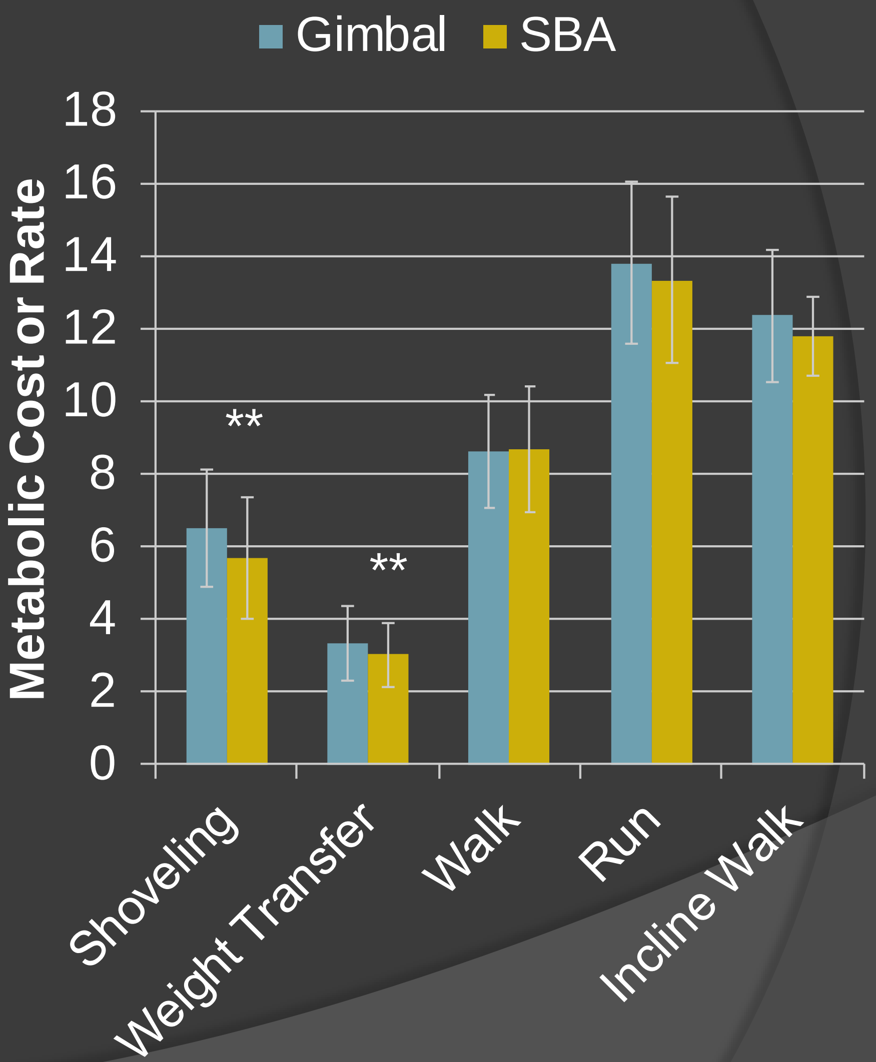
Methods

- Ten subjects

  (7 men, 3 women, 38 ± 9.3 yrs, 178.1 ± 9.3 cm, 79.5 ± 15.7 kg)
- Offloaded to 1/6-g for both conditions
- Tasks included overground and treadmill ambulation, picking up objects, shoveling, postural stability, range of motion testing, recovery from kneeling and prone positions
- Metabolic, biomechanical, and/or subjective data were collected based on task

Results - Metabolic

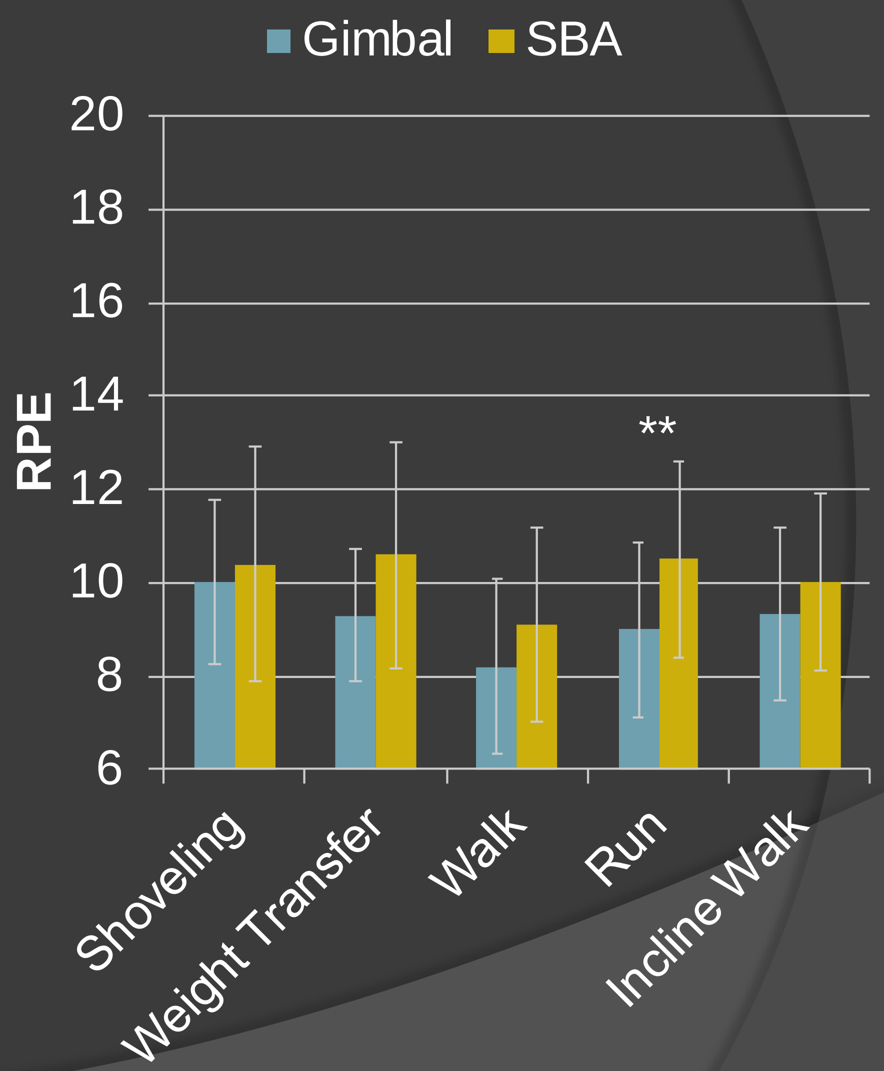
- Little to no difference between conditions
- General trend is for SBA < Gimbal
- Shoveling and weight transfer were statistically significant, but not practically significant
- May be learning effects
  - Gimbal was 2nd
  - SBA was 4th (last)
  - Logistical issue based on system set-up



** statistically significant (paired t-test, $p<0.05$)

Results - RPE

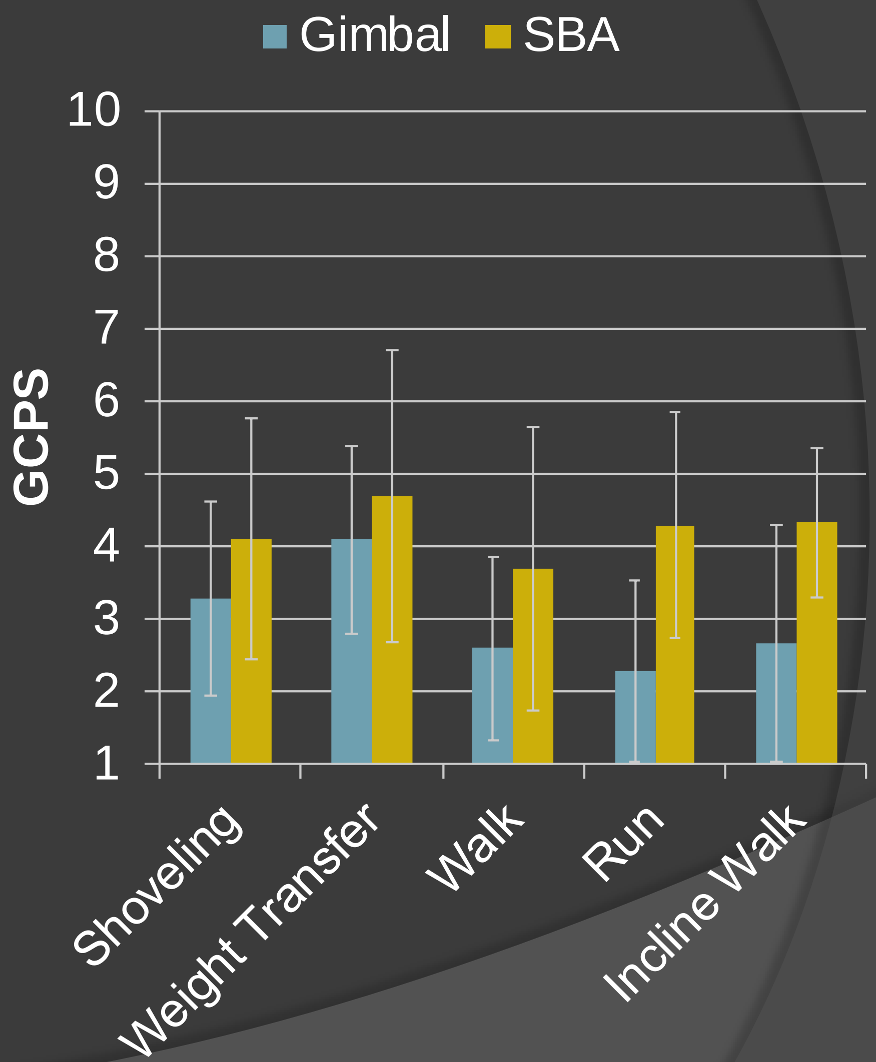
- General trend is for Gimbal < SBA
- Opposite of metabolic findings
- Although metabolically equal, subjects perceive the SBA as higher effort



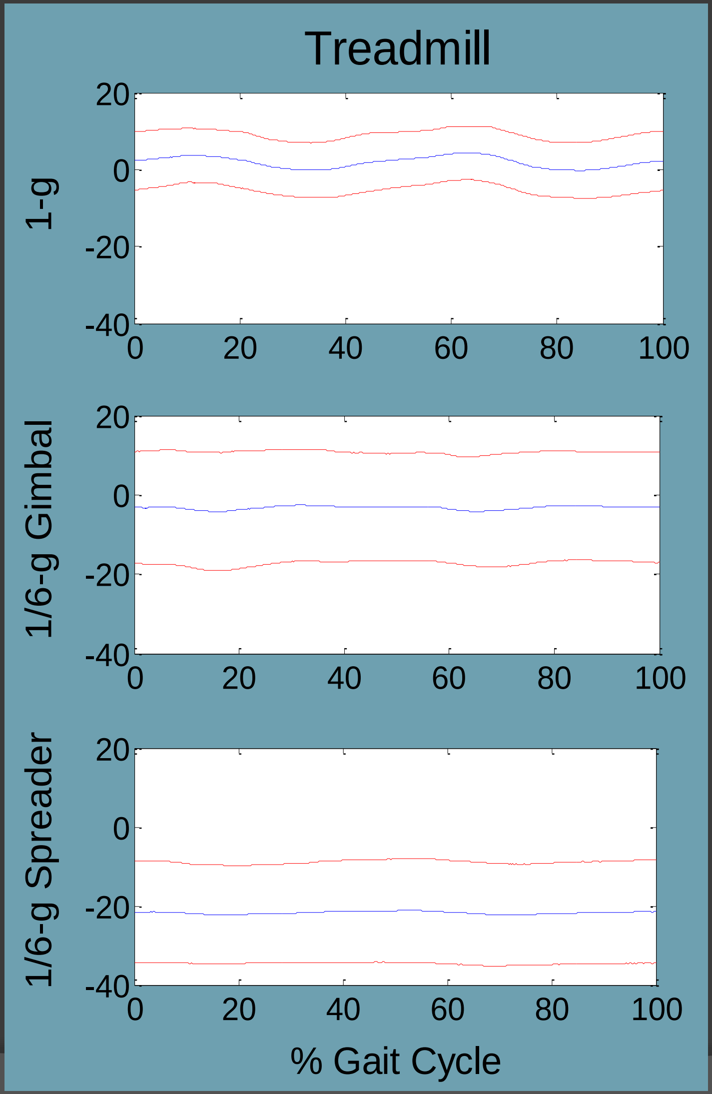
** statistically significant (paired t-test, $p<0.05$)

Results - GCPS

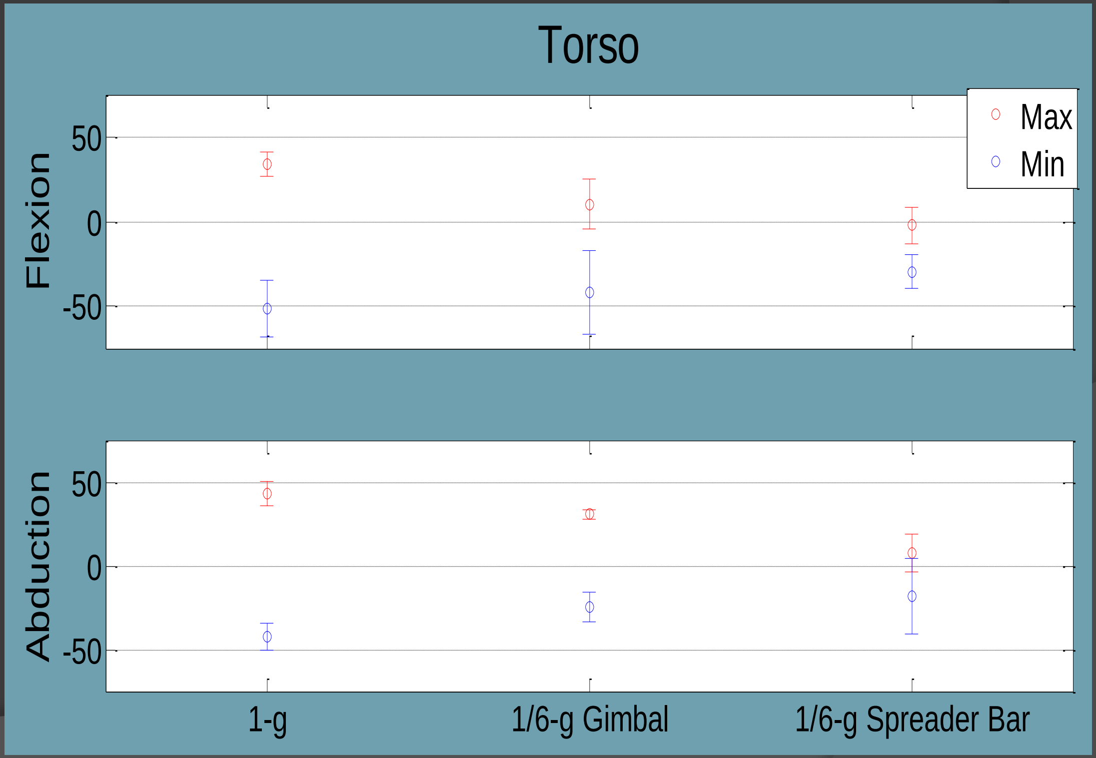
- General trend is for Gimbal < SBA
- Opposite of metabolic findings
- Although metabolically equal, subjects perceive the SBA as requiring more compensation



Results - ROM



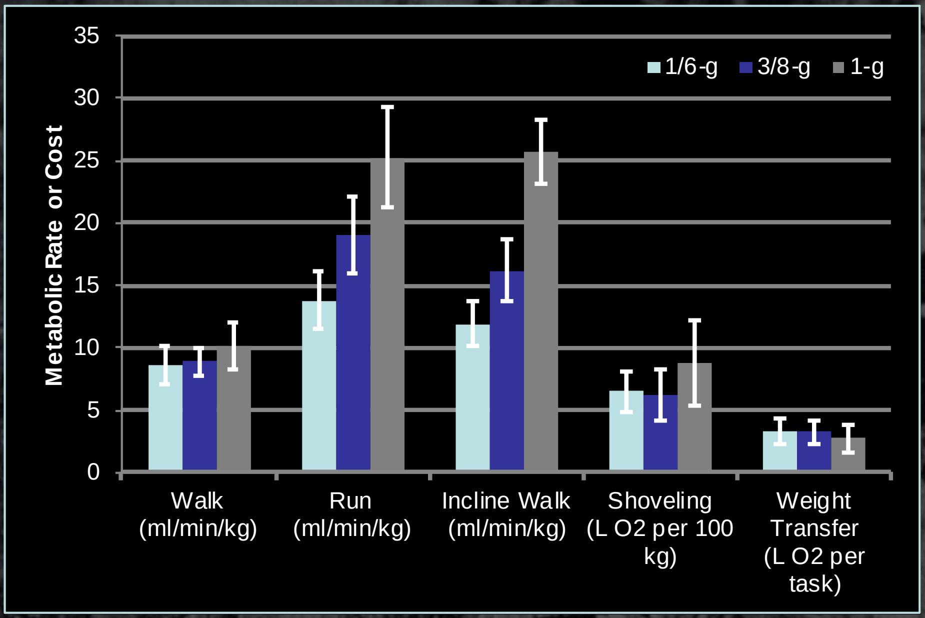
- Torso angle and ROM was different between gimbal and SBA
- SBA harness and straps restricted torso ROM

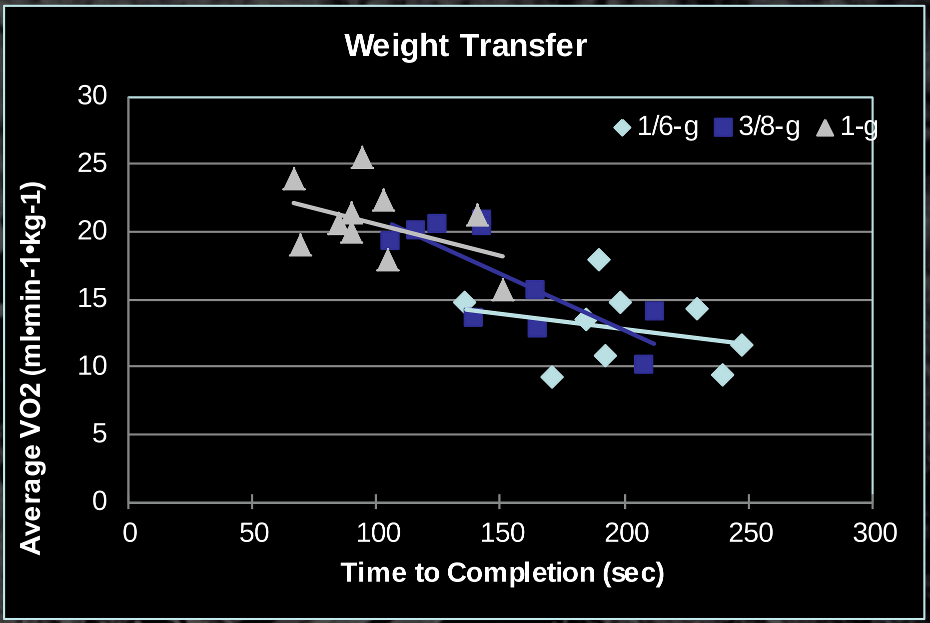


Discussion

- The gimbal is a step in the correct direction, but there are still notable differences between 1-g and 1/6-g in the gimbal
- Although the SBA did not significantly affect metabolic parameters, it clearly restricts torso ROM and forces a different strategy that is less like 1-g

Task Selection is Critical (Unsuited ARGOS Testing)





- To determine if gravity level has an effect on the metabolic performance of EVA tasks:
  - Select tasks that require the subject to work vertically against the force of gravity
  - For non-steady state tasks, an additional measurement such as time to completion is important to evaluate performance as metabolic rate/cost alone may not be sufficient

Haughton Mars Project

Desert RATS

Neutral Buoyancy Laboratory (NBL)

NEEMO

1-G FIELD & UNDERWATER ANALOGS

THE EFFECTS OF TERRAIN AND NAVIGATION ON HUMAN EXTRAVEHICULAR ACTIVITY WALKBACK PERFORMANCE ON THE MOON

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Jeff A. Jones, M.D.
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Aerospace Medical Association
May 12-15, 2008
Boston, Massachusetts, USA

Background and Primary Objective

- Results of the EVA Walkback Test showed that 6 male astronauts were able to ambulate 10 km on a level treadmill while wearing a prototype EVA suit in simulated lunar gravity.

- However, the effects of lunar terrain, topography, and real-time navigation on ambulation performance are unknown.

- Primary objective: To characterize the effect of lunar-like terrain and navigation on VO_2 and distance traveled during an unsuited 10 km (straight-line distance) ambulatory return in earth gravity.

Test Protocols

- Haughton Mars Project (HMP) Walkback
  - 10 km “as the crow flies”
  - GPS navigation
  - Rapid but sustainable pace
    - <85% predicted max HR
  - No time limit or route limitations
  - 3 separate routes
- Matched Treadmill Control
  - Speed/grade/distance matched to HMP Walkback
  - 1 minute average (speed/grade)
  - Matched to SW Highland Route
- Level Treadmill Control
  - Distance matched
  - Rapid but sustainable pace
    - <85% predicted max HR
  - No time limit
  - Subjects blinded to speed

HMP Walkback Protocol

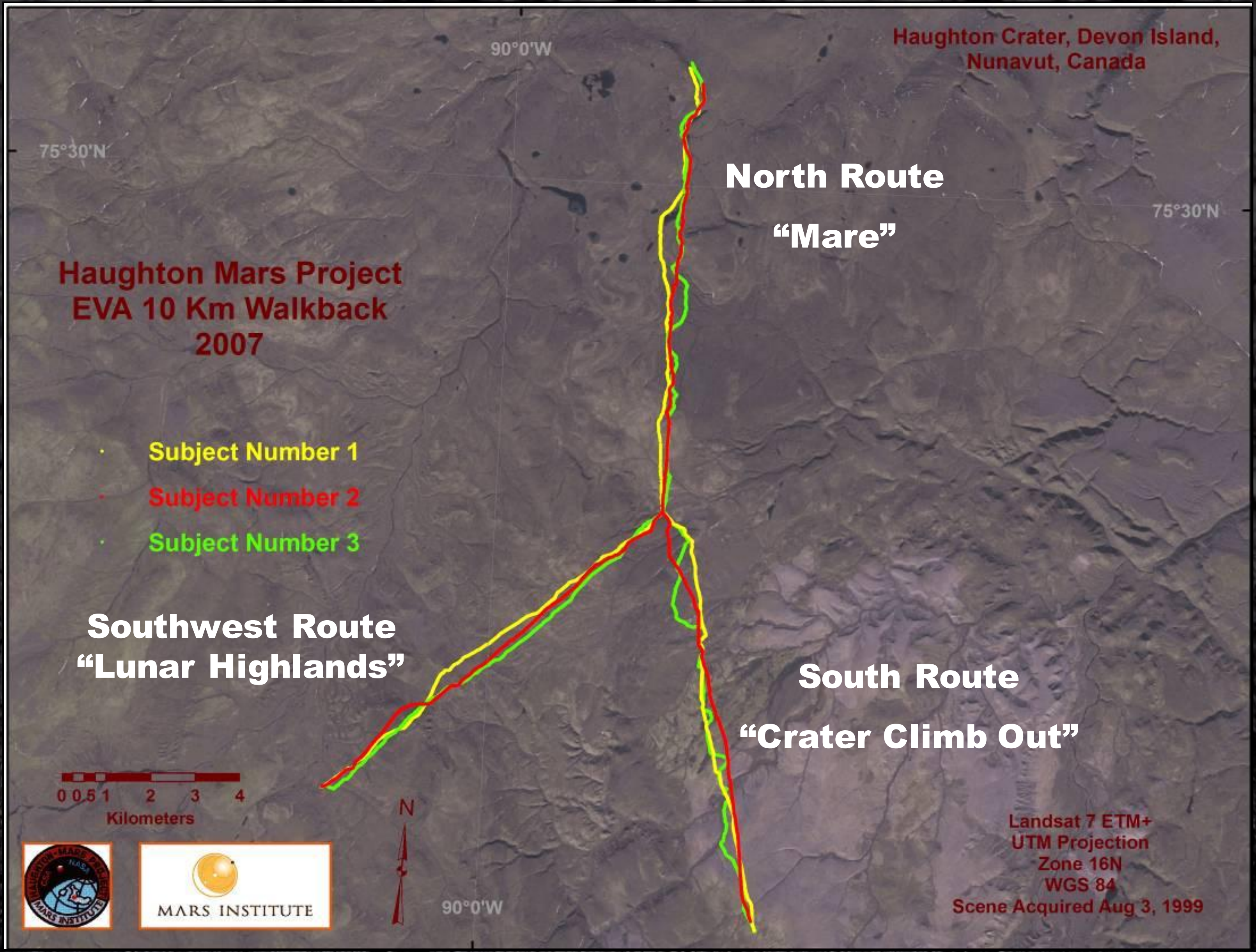
Out

- Synchronize GPS with base
- Calibrate Cosmed
- Traverse departs
- Test subject wears backpack (Cosmed, GPS, water) on ATV1
- Two people double up on ATV
- 5-6 ATVs together

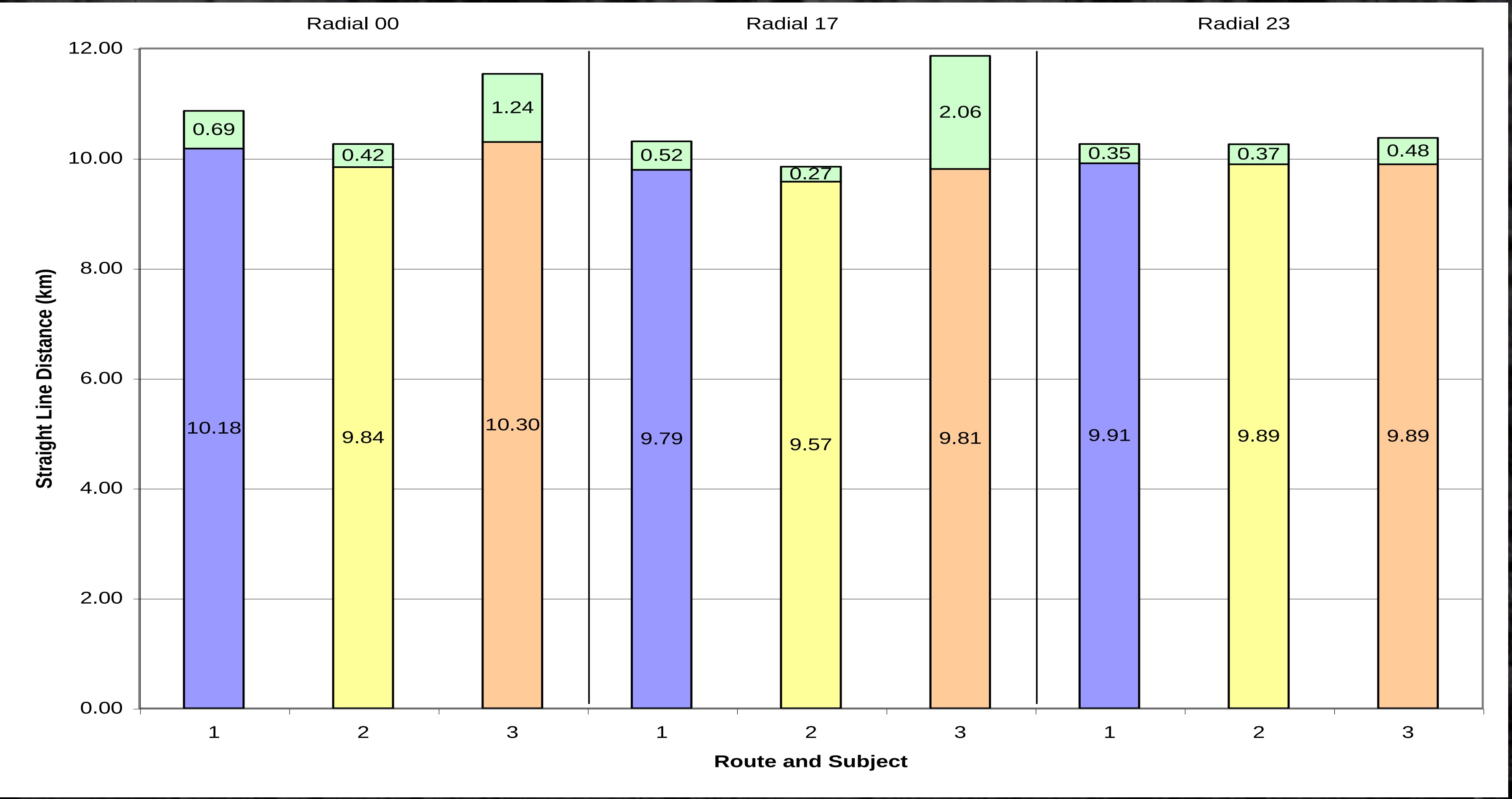
In

- Test checklist completed: start called
- Formed two return groups:
  - Each group: GPS, maps, >2 radios and batteries, one firearm
  1. Roving group: videotaped test
     - 2 ATVs (video & guide/protection)
  2. Test group: tracked subject
     - Subject on foot, trailed by guide/others
     - Medical kit, emergency food and water

Route Selection



HMP Walkback Results



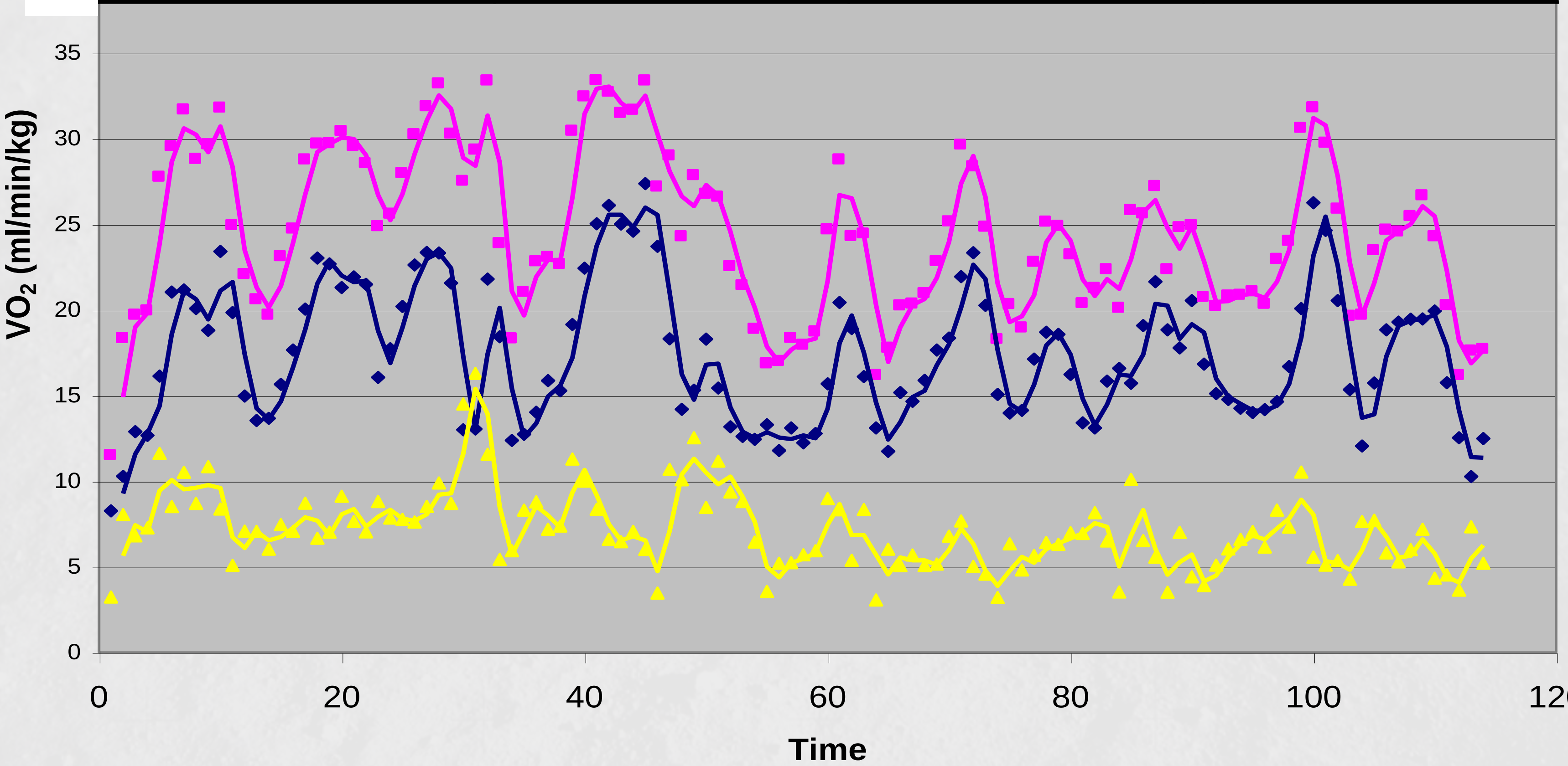
- Average time 126.5 ± 28.7 min (mean ± SD)……...[96 min for EWT]
- Average VO_2 27.8 ± 5.1 $mL \cdot kg^{-1} \cdot min^{-1}$…………………[24.8 for EWT]
- Straight line distance 9.91 ± 0.22 km
- Actual distance was 10.61 ± 0.61 km (7% increase)

HMP Walkback Speed/Grade Matched Control Trial

- Speed/grade matched to the best 1-min average from field
- Speed/grade adjusted manually every minute
- Clothing and boots similar to field trials
- Weighted vest used to account for weight differences
- -10° to 30° available
  - Within this band > 98% of time

Results: Field vs. Matched Control

Summary (n=3)	HMP	JSC	ΔVO_2
Avg VO_2 ($mL \cdot kg^{-1} \cdot min^{-1}$)	26.9 ± 6.4	17.1 ± 4.9	9.8 ± 3.8

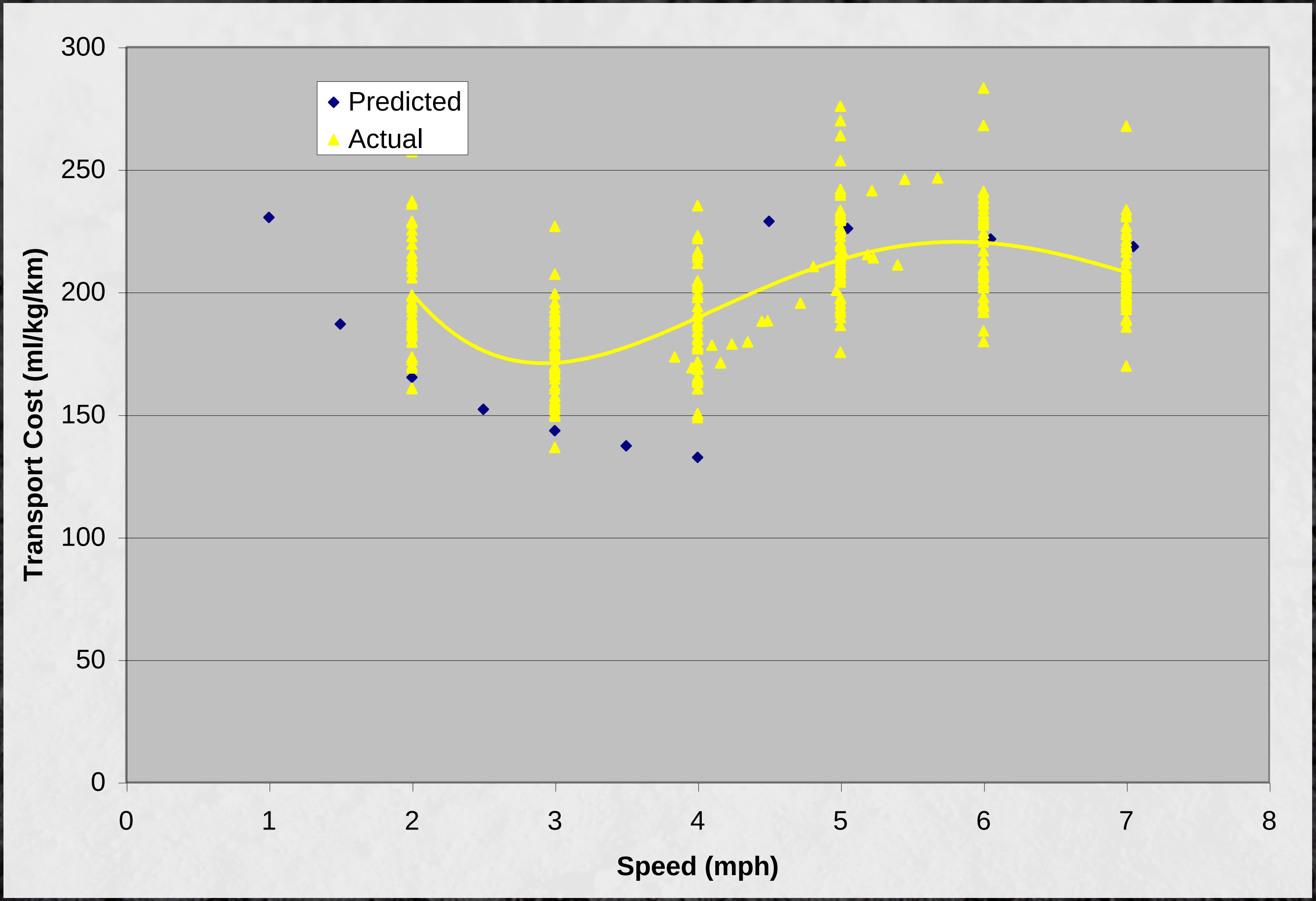


Level, Self-selected Speed Control Trial

Total VO_2 (L)	JSC Level Control	JSC Matched Control	HMP
Sub 1	208	173	243
Sub 2	208	171	279
Sub 3	174	149	249
Avg	197	164	257

- Level treadmill
- Distance matched
  - Noted 10 km stats also
- No time limit
- Speed blinded to subject
- Self-selected speed
  - Can change at any time
- Similar clothing/boots to field trials
- Weighted vest used to account for weight differences

1-g Transport Cost



Data from JSC Locomotion Study, Cosmed/Parvo Validation and EWT 1g trials

Putting in All Together

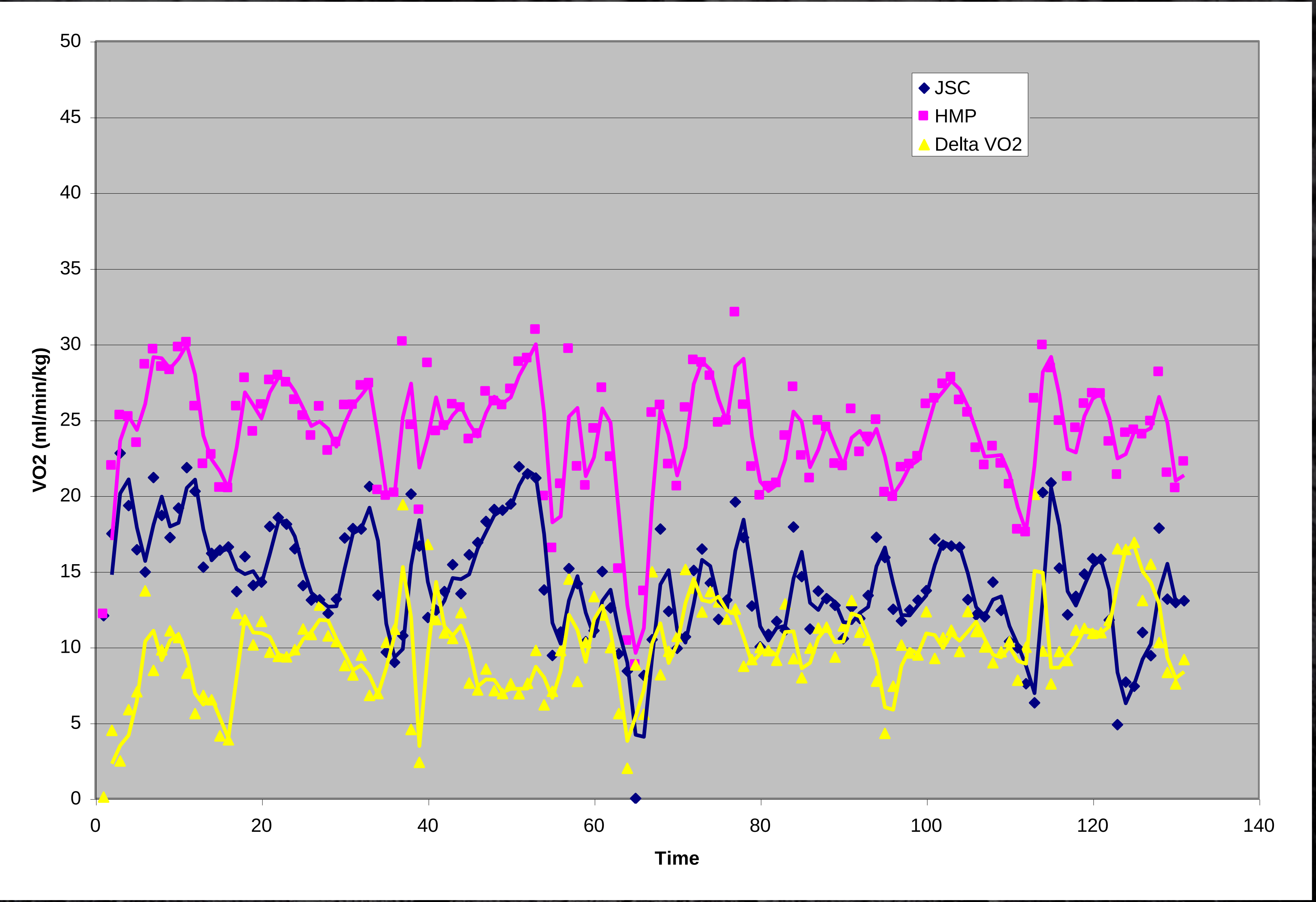
- EWT results need re-evaluation
- Terrain and navigation:
  - ↑ VO_2 by 56% avg (range 41-67%)
  - ↑ distance by 7% (up to 21%)
- Incline/decline:
  - Story is unclear
  - 1-g transport cost u-shaped
  - Suited 1/6-g incline metabolic cost shows energy recovery

Implications

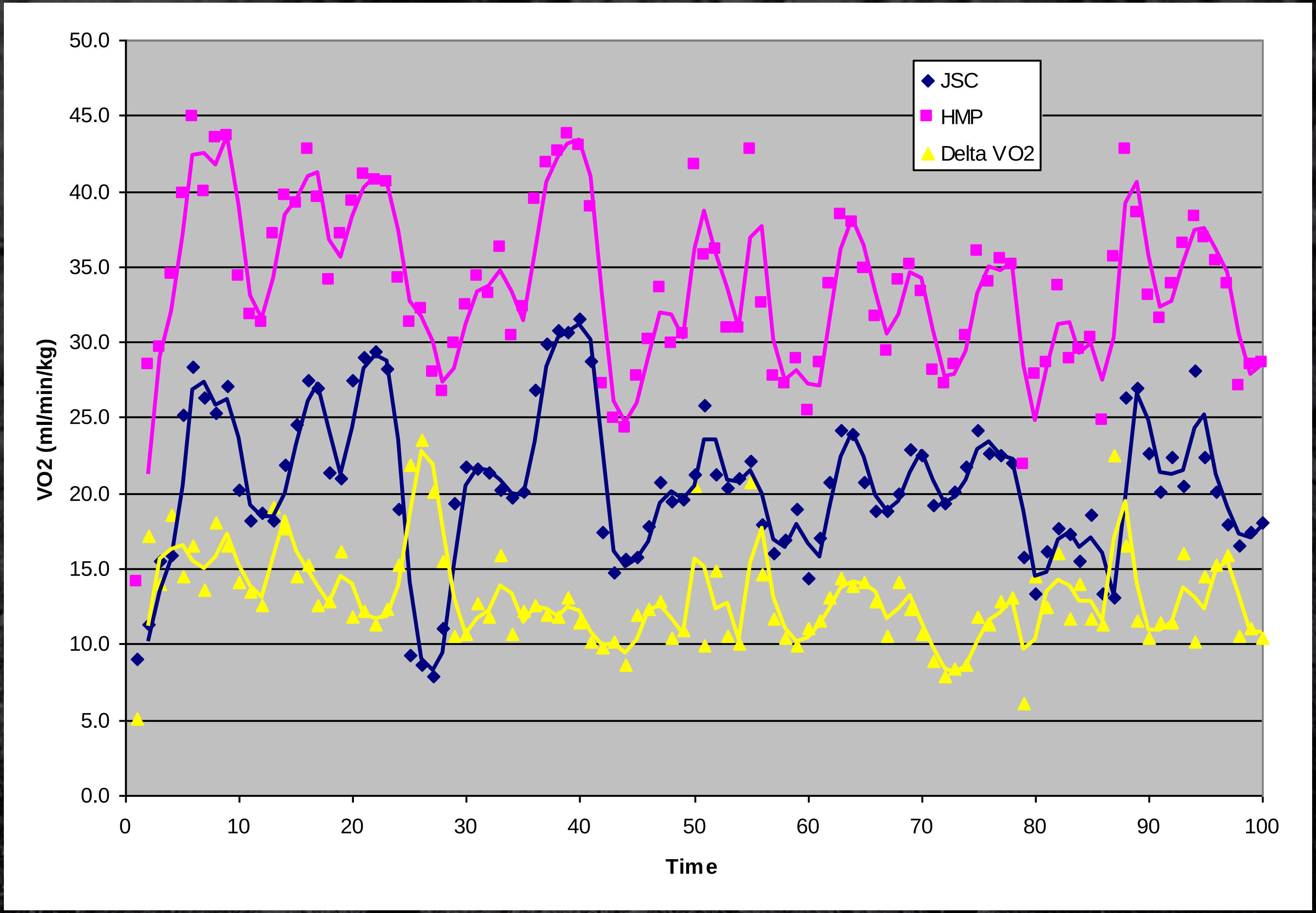
Forward Work

- Increase data pool
  - Complete remaining 6 control trials
  - Increase # of walkbacks
- Does this carry over to 1/6 g?
  - Gait differences (contact time, ground reaction force, stride length, cadence)
  - Slope and soil characterization
  - HMP subjects complete 10-km suited walkback
  - Speed/grade matched 10-km walkback profile
  - Speed matched only 10-km walkback profile
  - Portable POGO

Back-up slides – Sub 3



Back-up Slides – Sub 2



DRATS 2008: Primary Hypotheses

1. Performance achieved during 1-day exploration/mapping/geological traverses using the Lunar Electric Rover (LER) will be equal to or greater the performance achieved during Unpressurized Rover (UPR) traverses, with less suit time.

2. The human factors and crew accommodations within the LER will be acceptable to support a 3-day exploration/mapping/geological traverse.

Study Design

- **Two 2-person EVA crews**
  - One astronaut per crew
  - One field geologist per crew
  - Only one crew performed the 3-day LER traverse

	1-day		3-day
Crew A	UPR Traverse UPR1A	LER Traverse LER1A	LER Traverse LER3A
Crew B	LER Traverse UPR1B	UPR Traverse LER1B	

- **For the purpose of UPR-LER comparisons, practically significant differences in metrics were prospectively defined for the testing of study hypotheses**
  - 10% difference in time, range and productivity metrics
  - Categorical difference in subjective human factors metrics

Example LER 1-day Traverse Timeline

	6:00	7:00		8:00			9:00				10:00		11:00		12:00	
EV1	Post sleep	DPC	PMC	2.0 SPR Power Up - 3.0 SPR Consumables Check	4.0 Undock	Checkout and Drive to Sta 1	Context Obs		Relocate Down Escarpment	Context Obs		Drive Along Escarpment	Drive West Away from BPLF	Drive South Along Marbled Unit	Drive to Sta 2 Midday Meal	Egress
EV2	Post sleep	DPC	PMC	2.0 SPR Power Up - 3.0 SPR Consumables Check	4.0 Undock	Checkout and Drive to Sta 1	Egress	Station 1 (A - Edge of BPLF)	Relocate Down Escarpment	Station 1 (B - Base of Escarpment)	Ingress	Drive Along Escarpment	Drive West Away from BPLF	Drive South Along Marbled Unit	Drive to Sta 2 Midday Meal	Egress

13:00		14:00		15:00			16:00		17:00		18:00			19:00			20:00
Station 2 (C - Vents)	Ingress	Drive to Station 3	Context Obs		Drive to Sta 4	Egress	Station 4 (E - Main BPLF)	Drive to Sta 5	Station 5 (F - Main Marbled)	Ingress	Drive to Hab	Docking	SPR Power Down	Post-EVA	DPC	PMC	Pre-Sleep
Station 2 (C - Vents)	Ingress	Drive to Station 3	Egress	Station 3 (D - Top of Flow)	Context Obs from Cheap Seat	Station 4 (E - Main BPLF)		Drive to Sta 5	Station 5 (F - Main Marbled)	Ingress	Drive to Hab	Docking	SPR Power Down	Post-EVA	DPC	PMC	Pre-Sleep

Scientific Productivity Metric

DESERT RATS 2008

Value of Traverse Objective

METRIC	DESCRIPTOR	DEFINITION
1	Low	Low anticipated scientific importance
2	Moderate	Moderate anticipated scientific importance
3	High	High anticipated scientific importance

PLRP Data Quality Scale

METRIC	DESCRIPTOR	DEFINITION
0	No Data	No Data Collected
1	Limited	Video and navigation did not support scientific observations and other relevant data was of limited use. Dive must be re-flown.
2	Adequate	Provides useful context and enables efficient return. Data is marginally publishable.
3	Significant	Quantitative data adequate to support specific documentation of scientific findings and yielding publishable results.
4	Exceptional	High quality video, navigation, and other quantitative data that supports and enhances scientific merit.

The Weighted Sum of Completed Traverse Objectives (WSCTO) metric enables absolute comparison of the productivity of different traverses in the same region. The metric is based on the Pavilion Lake Research Project Scales of Science Merit and Data Quality, but scores are applied to individual traverse objectives rather than a traverse as a whole.
Weighted Sum of Completed Traverse Objectives = $\sum$ VTO (n) x DQ (n)

Lunar Electric Rover

Lunar Electric Rover

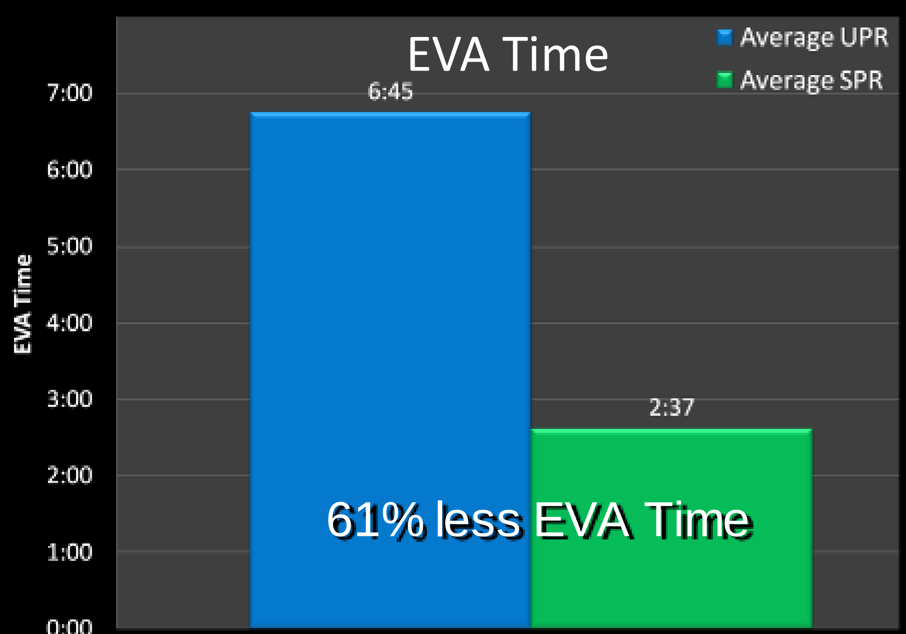

LUNAR ELECTRIC ROVER

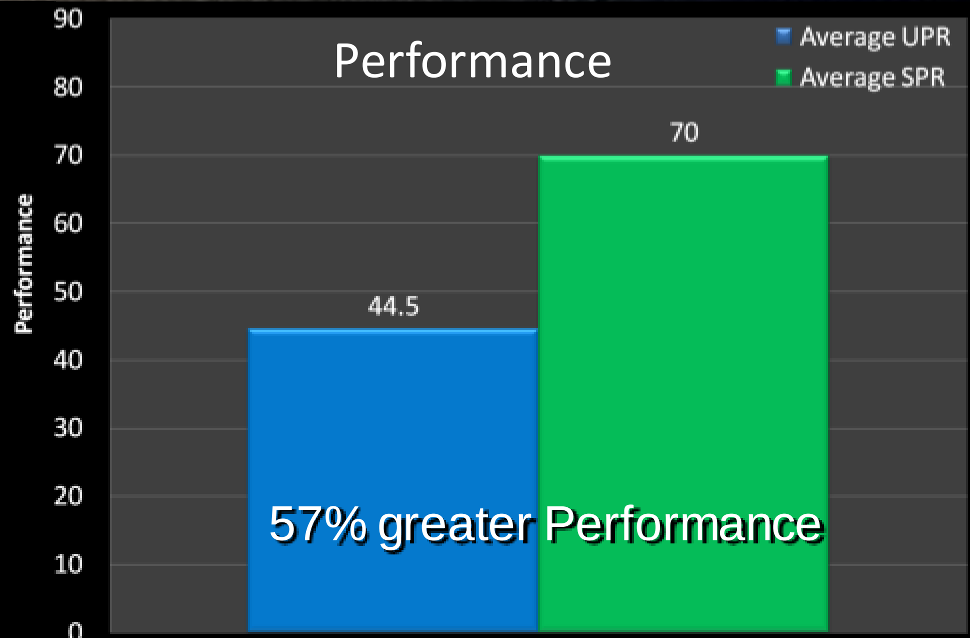
Lunar Electric Rover

Hypothesis 1: Performance achieved during 1-day exploration/ mapping/ geological traverses using the Lunar Electric Rover (LER) will be equal to or greater the performance achieved during Unpressurized Rover (UPR) traverses, with less suit time.

Data Collection: Performance and EVA Suit Time data collected during 2x 1-day UPR traverses and 2x 1-day LER traverses

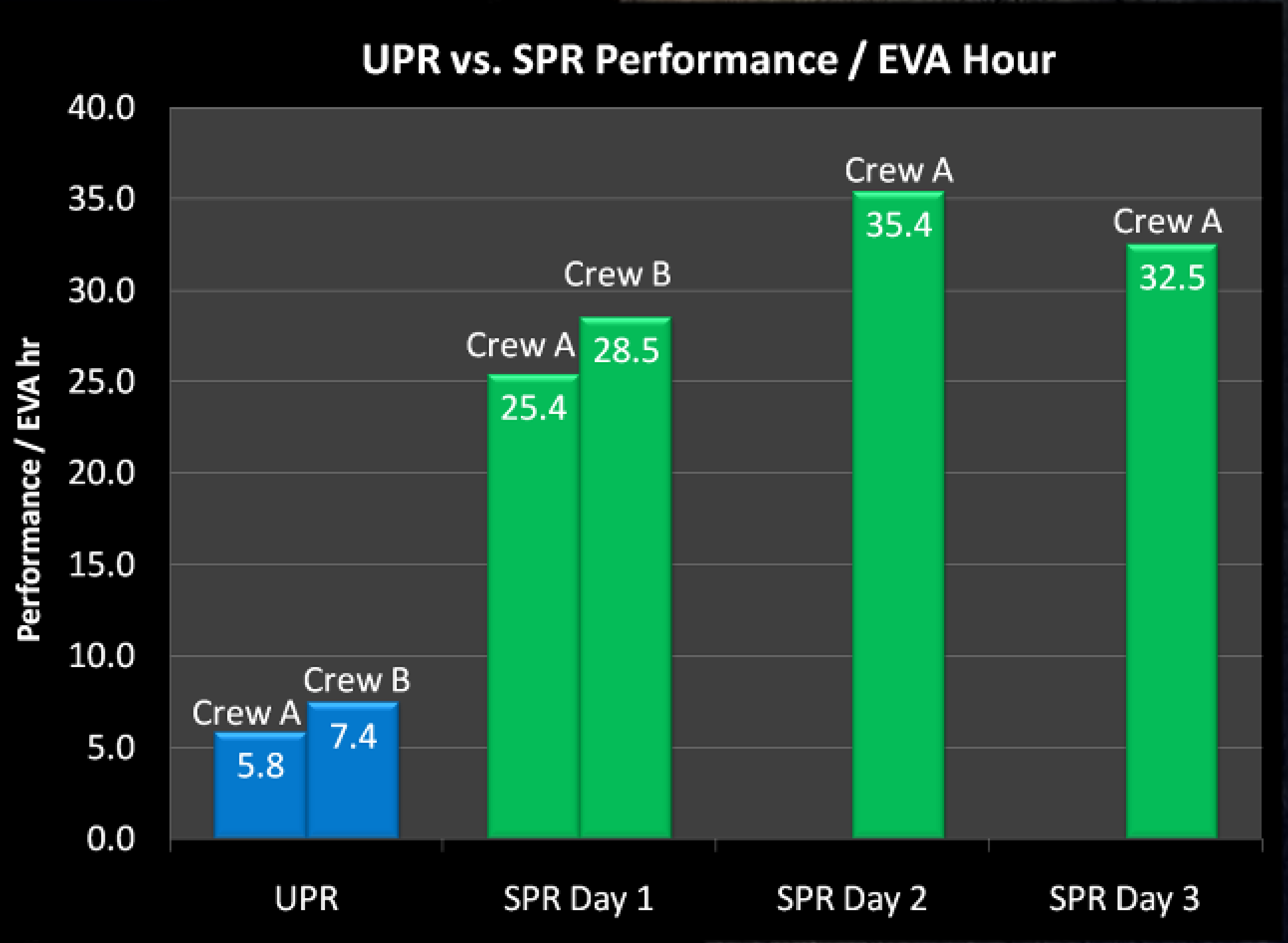
Results:





➔ **HYPOTHESIS ACCEPTED**

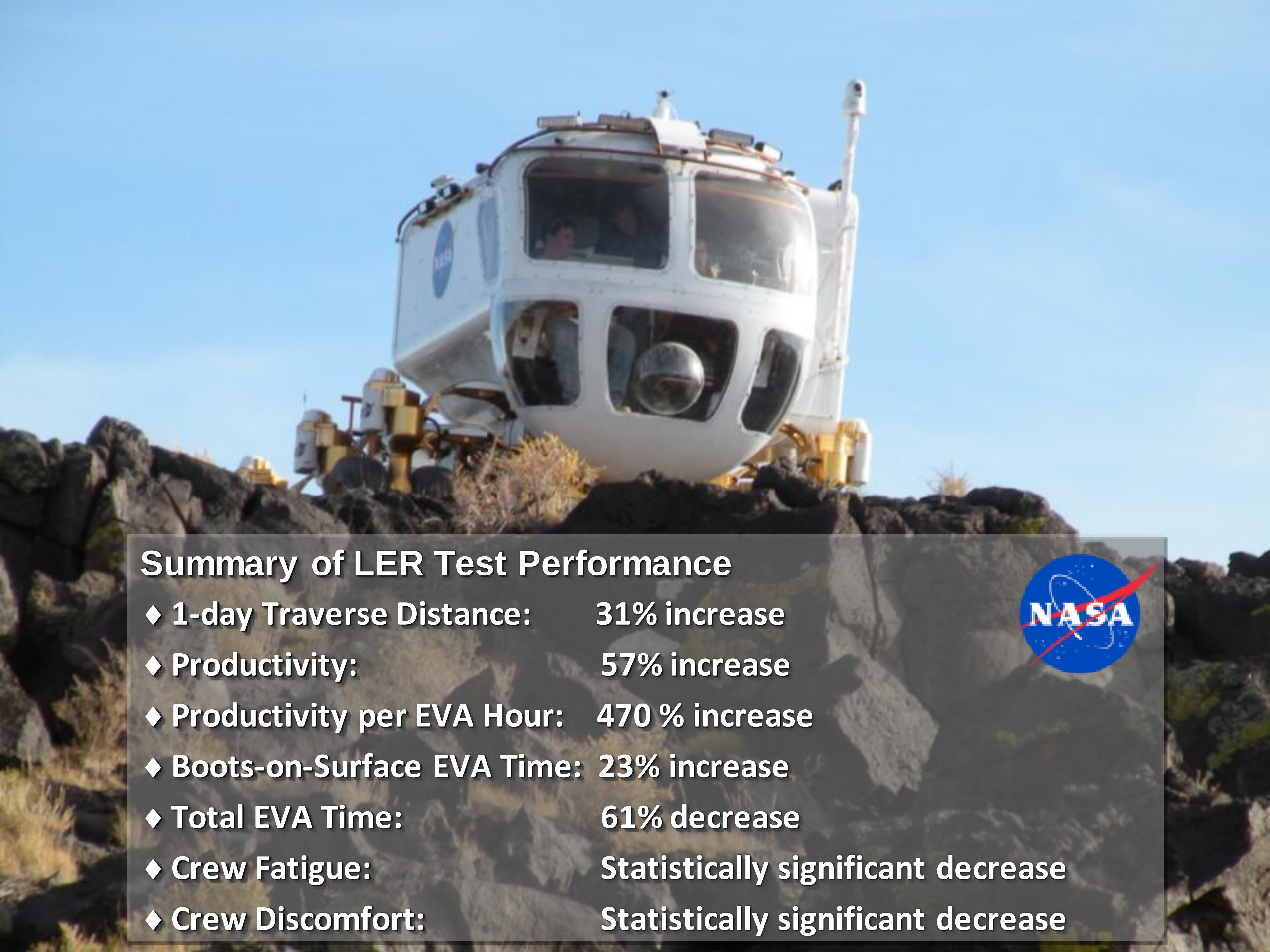
Hypothesis 1: Performance achieved during 1-day exploration/ mapping/ geological traverses using the Lunar Electric Rover (LER) will be equal to or greater the performance achieved during Unpressurized Rover (UPR) traverses, with less suit time.



➔ **HYPOTHESIS ACCEPTED**

Comments: LER performance per EVA hr = 3.4 to 6.1 x greater than UPR

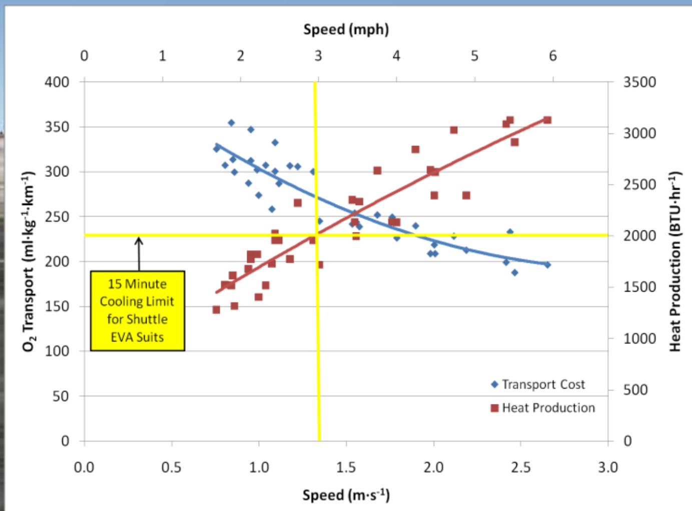
<u>Mean: 4.7 x more productive per EVA hr than UPR</u>

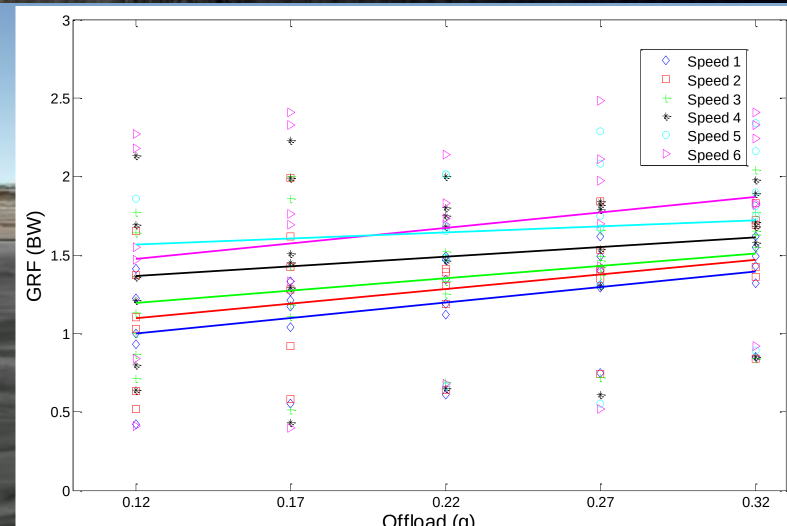


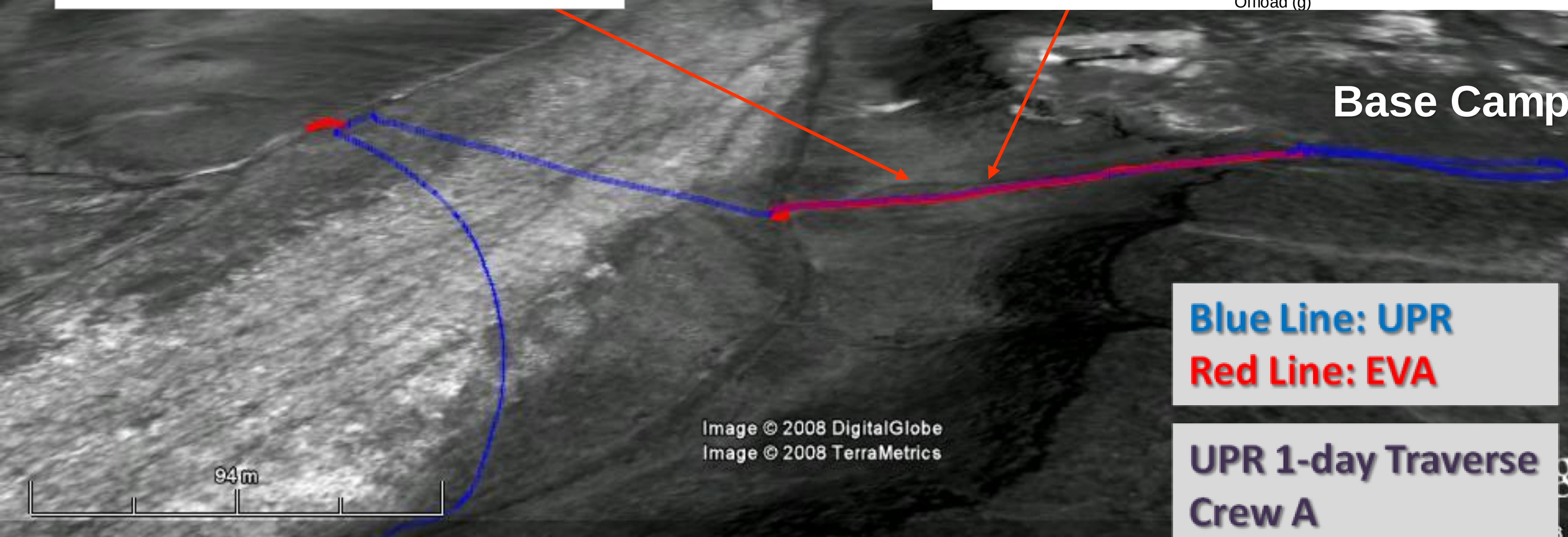
Summary of LER Test Performance

♦ 1-day Traverse Distance:	31% increase
♦ Productivity:	57% increase
♦ Productivity per EVA Hour:	470 % increase
♦ Boots-on-Surface EVA Time:	23% increase
♦ Total EVA Time:	61% decrease
♦ Crew Fatigue:	Statistically significant decrease
♦ Crew Discomfort:	Statistically significant decrease

Combining Field Operational Concept Data with Laboratory Physiological Data







NEEMO/NBL CG Studies

NEEMO

NBL

Gravity compensation and performance scale (GCPS) ratings and time to task completion were collected

- GCPS ratings are based on the level of operator compensation required in partial gravity compared to performing the same task, unsuited, in 1-g
- On this 10 point scale, a rating of 2 is equal to 1-g performance and larger numbers indicate perceived increases in the amount of subject compensation required to achieve desired performance

National Aeronautics and Space Administration

Metabolic Energy Expenditures During Extravehicular Activity: Spaceflight *Versus* Ground-based Simulation

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Johnny Conkin, Ph.D.[2]
Michael Gernhardt, Ph.D.[3]
Ramachandra Srinivasan, Ph.D.[1]

[1] Wyle, Houston, TX; [2] Universities Space Research Association, Houston, TX; [3] NASA Johnson Space Center, Houston, TX

www.nasa.gov

Metabolic Data

- Collected at the Sonny Carter Training Facility's Neutral Buoyancy Lab (NBL)
- To establish a baseline
  - For each crewmember
  - For each Extravehicular Activity (EVA)
    - EVA Acceptance Test (EVAAT) or Final

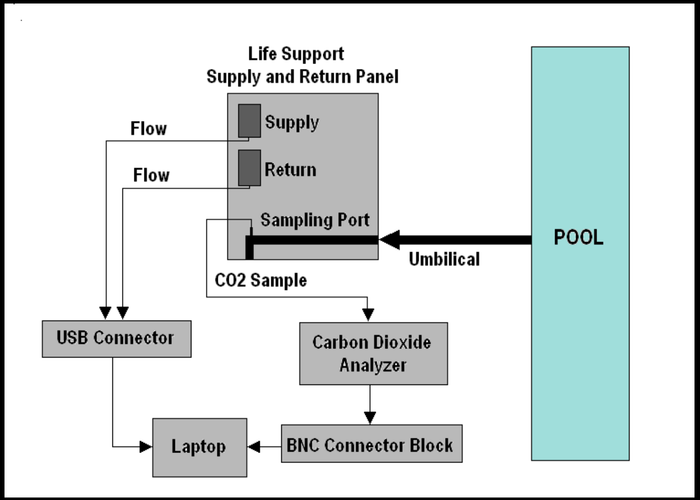
Ground-based Data

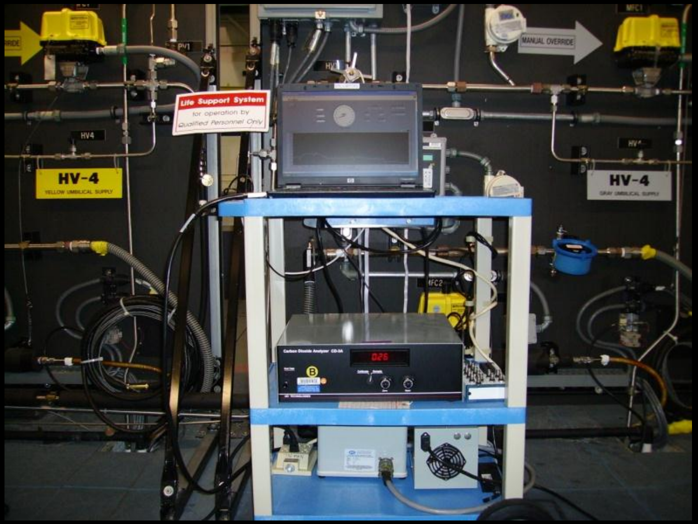
Flight Data

- Monitored during flight
- Processed postflight
- Met rates compared to NBL baseline data

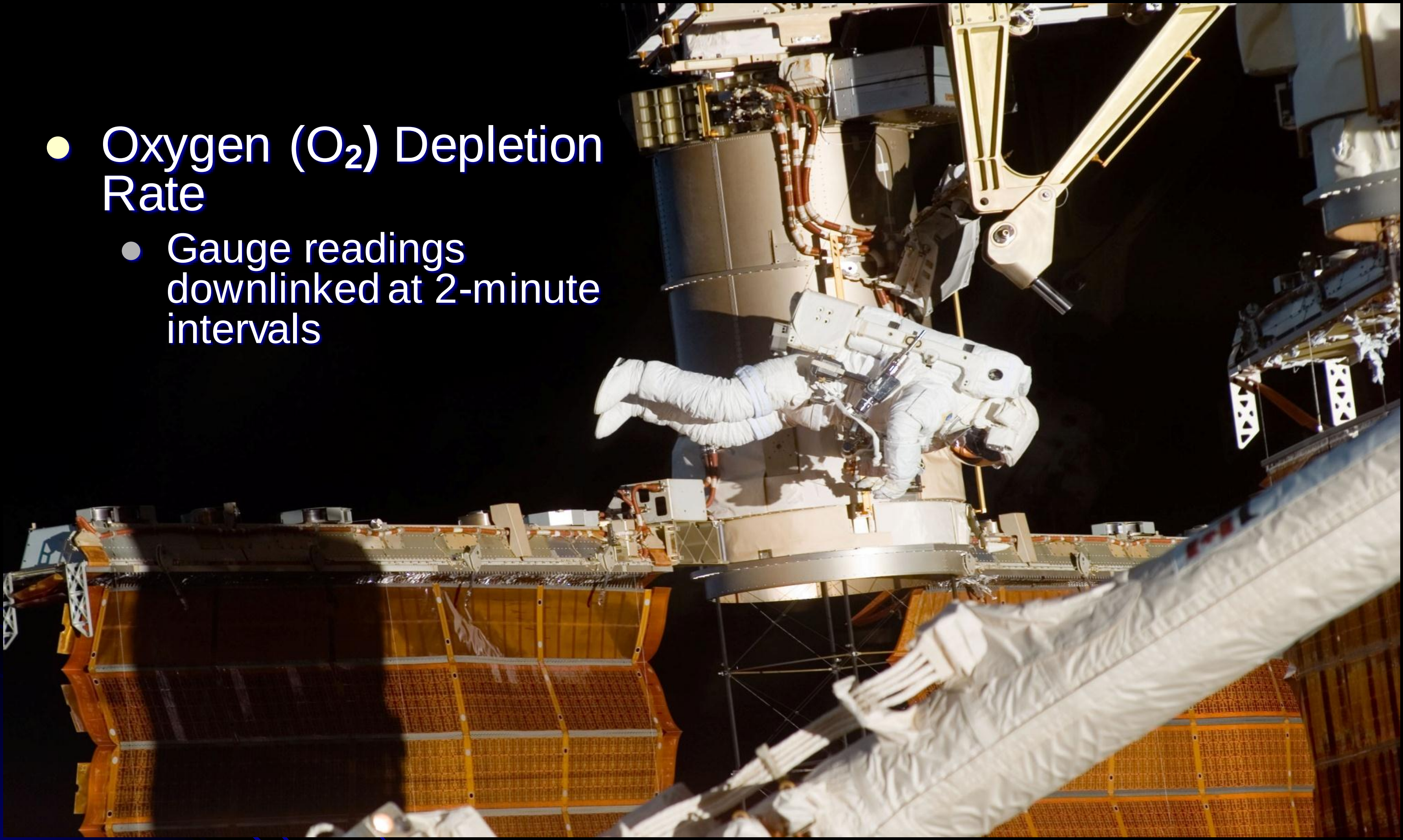
Collection Methods – NBL

- Carbon Dioxide (CO_2)
  - Sampled from return umbilical before venting out
  - Concentration measured using a CO_2 analyzer
- Gas Flow
  - Digital outputs from panel flow meters
  - Both supply and return flow rates measured



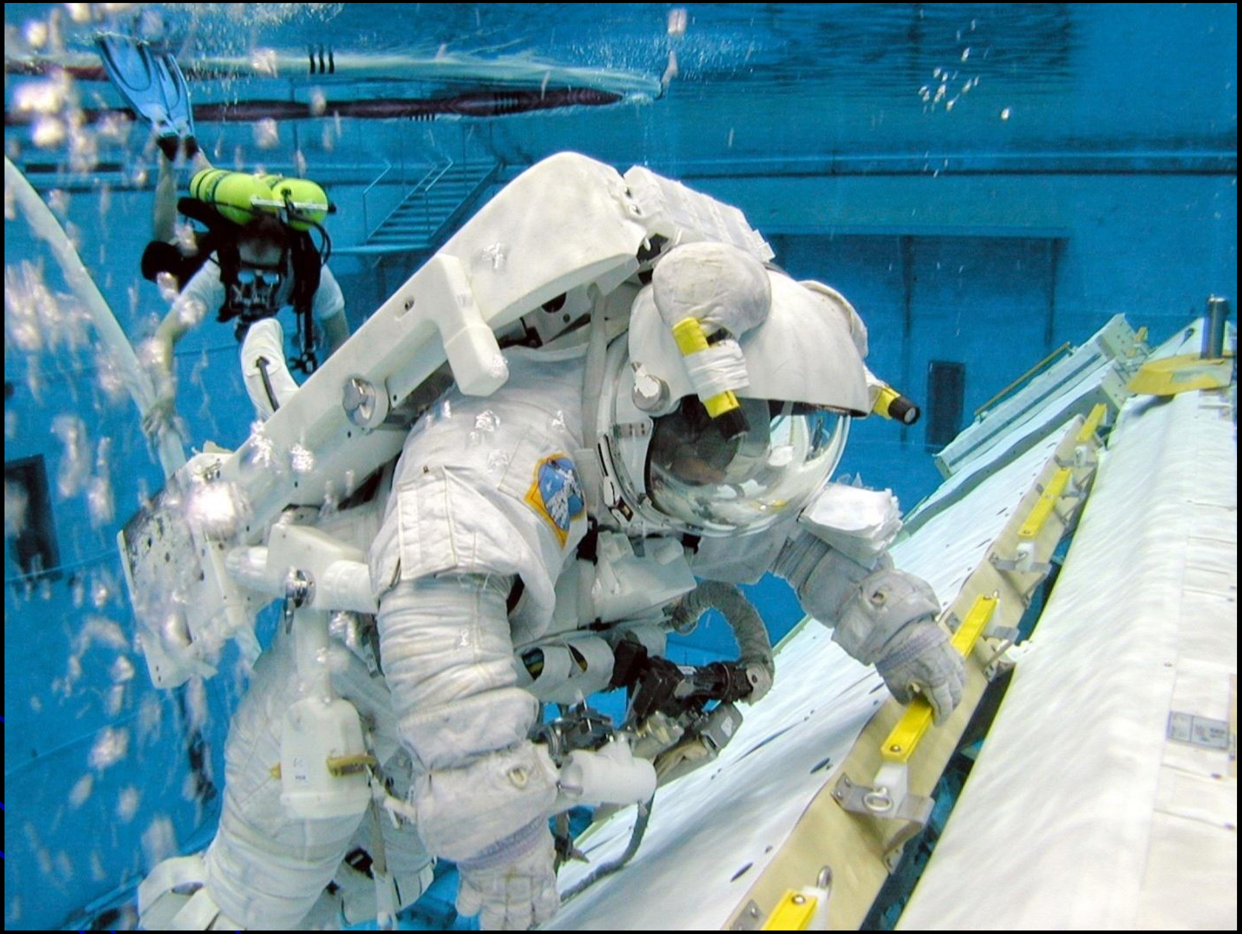


- Oxygen (O_2) Depletion Rate
  - Gauge readings downlinked at 2-minute intervals



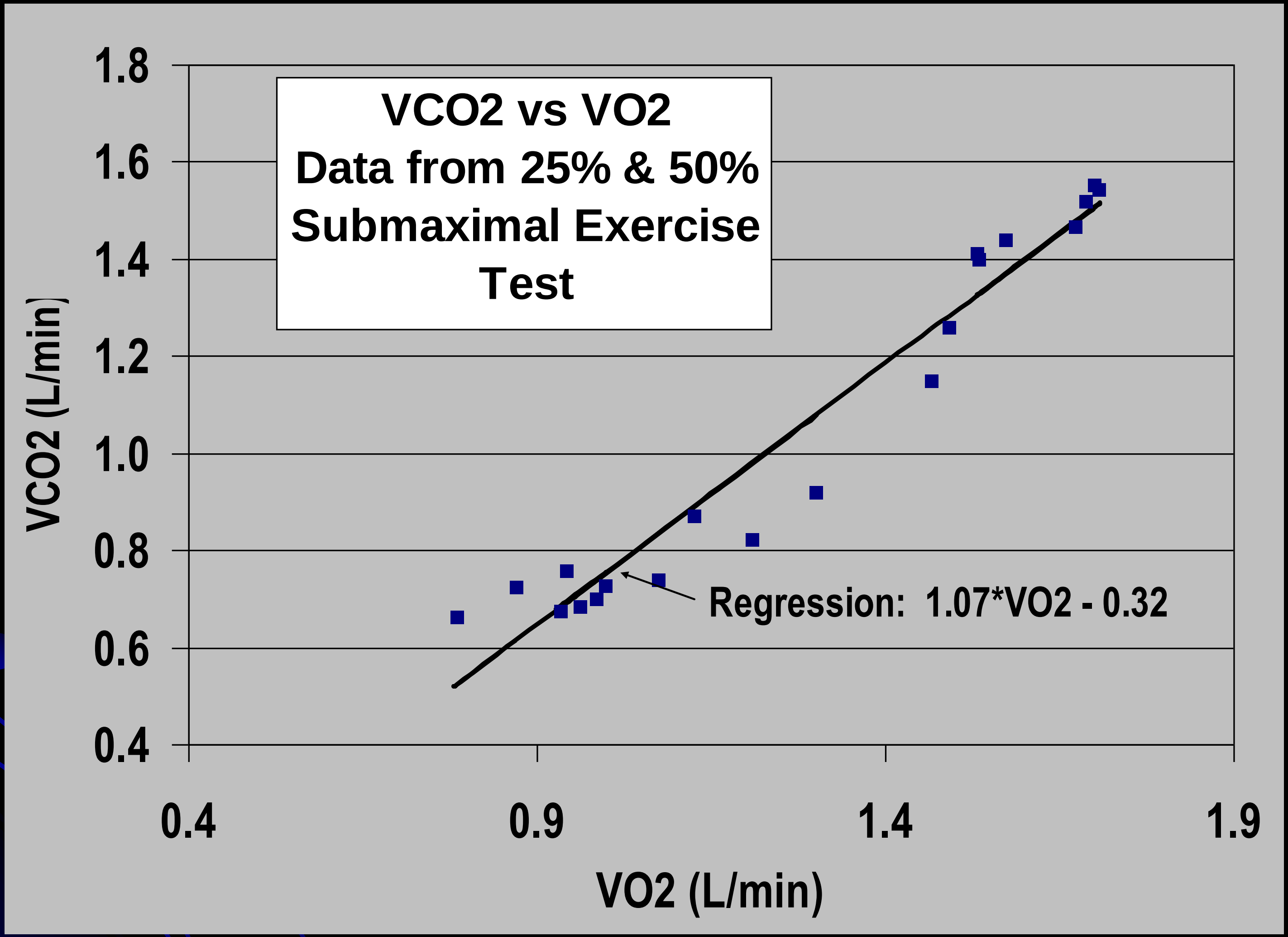
Collection Methods - Flight

VCO_2 = (Flow Rate) x (CO_2 Concentration)



Calculations

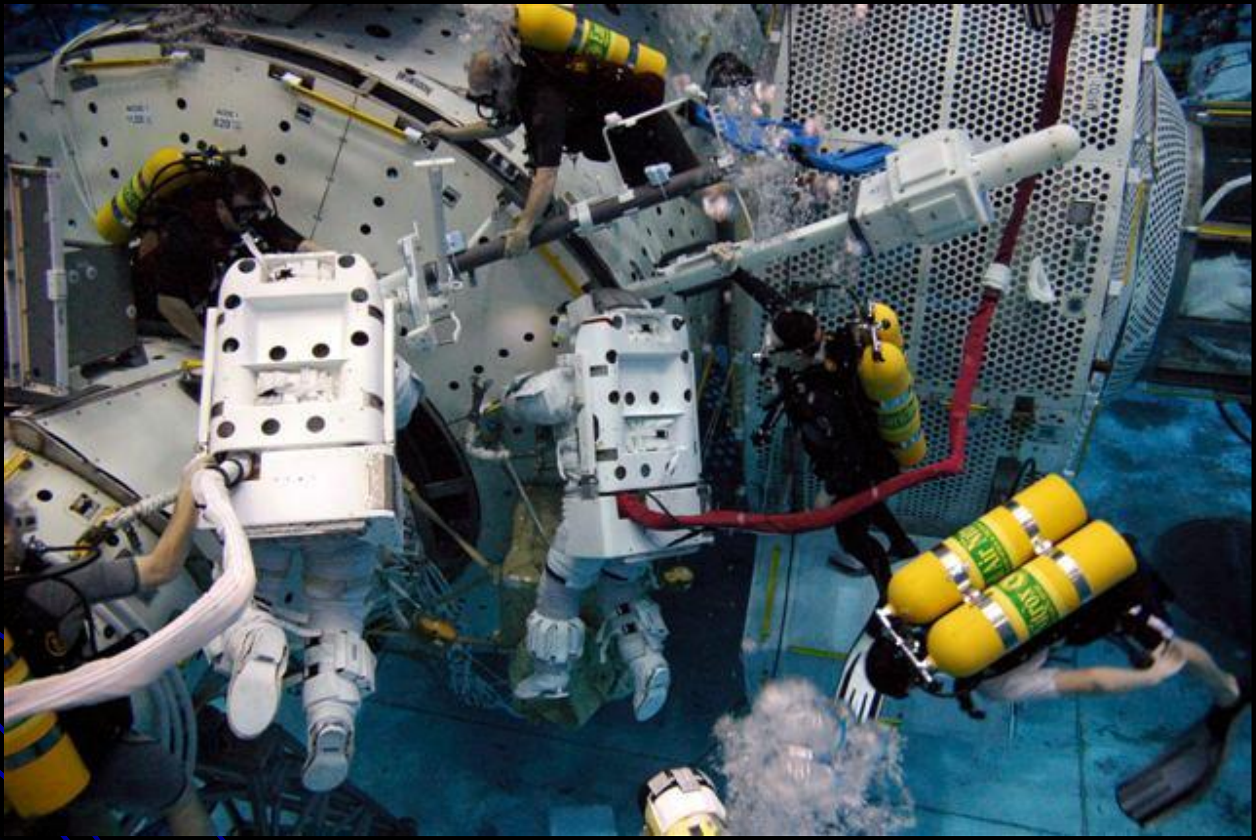
$VCO_2 = m \times (VO_2) + b$



Regression

Met Rate (kcal/hr) =

$$236.5 \times VO_2\ (L/min) + 66.6 \times VCO_2\ (L/min)$$



Weir Equation

O_2 Depletion Rate (psi /min) = 2.13 x VO_2 (L/min)

O_2 Usage

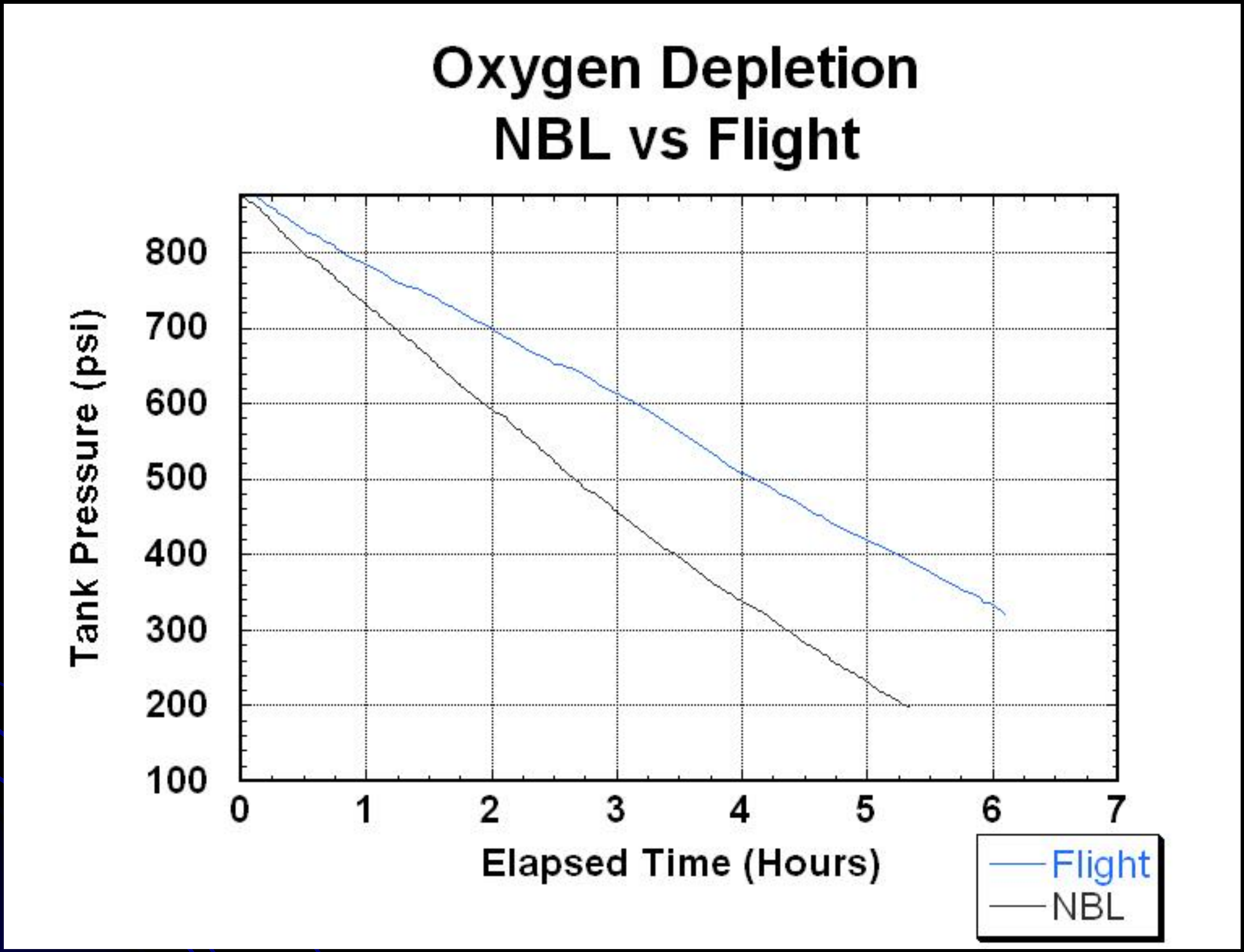
Task Analysis

Metabolic Rate - Task Analysis

STS-118 EVA 1

Subject ID Number: 2741

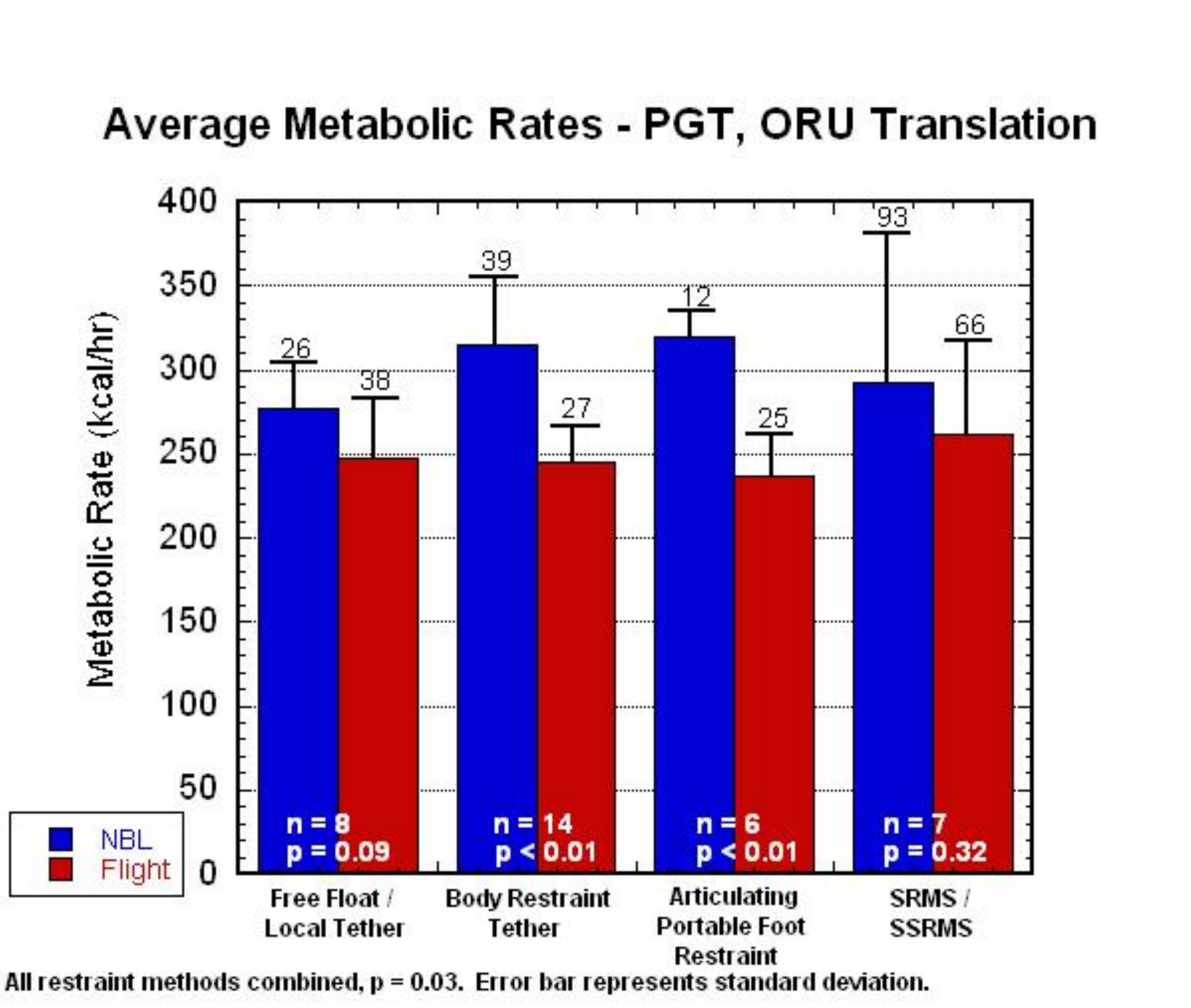
Activity	Time (h:mm)	Met Rate (Kcal/hr)	Met Rate (BTU/hr)	ΔTank Pr. (psi)	Tank Pr. (psi)
Post Depress/Egress/Setup	0:00			0	850
Min		143.18	568.14		
Max		564.39	2239.50		
Average		383.93	1523.42		
O2 depletion				69.81	
S5 to S4 Launch Locks	0:25				780.19
Min		212.97	845.06		
Max		616.03	2444.41		
Average		395.79	1570.48		
O2 depletion				63.32	
S5 Install	0:47				716.87
Min		202.19	802.29		
Max		590.91	2344.73		
Average		404.88	1606.55		
O2 depletion				188.47	
PVRGF Relocate	1:51				528.4
Min		123.03	488.18		
Max		689.56	2736.17		
Average		330.89	1312.99		
O2 depletion				108.2	
S5 to S4 Umbilicals	2:36				420.2
Min		246.91	979.74		
Max		571.11	2266.16		
Average		410.11	1627.31		
O2 depletion				122.3	
S5 Cleanup	3:17				297.9
Min		132.27	524.85		
Max		647.32	2568.57		
Average		387.83	1538.92		
O2 depletion				110	
PVR Retract and Cinch	3:56				187.9
Min		183.75	729.12		
Max		522.24	2072.25		
Average		328.09	1301.87		
O2 depletion				71.59	
Cleanup/Ingress/Prerepress	4:26				116.31
Min		154.78	614.17		
Max		565.53	2244.02		
Average		327.55	1299.71		
O2 depletion				47.62	
	4:46				68.69
Average Met Rate:		375.63	1490.49		
Peak Met Rate:		689.56	2736.17		
Total O2 depletion:				781.31	
Total Met energy expenditure:		1790.49 Kcal	7104.66 BTU		



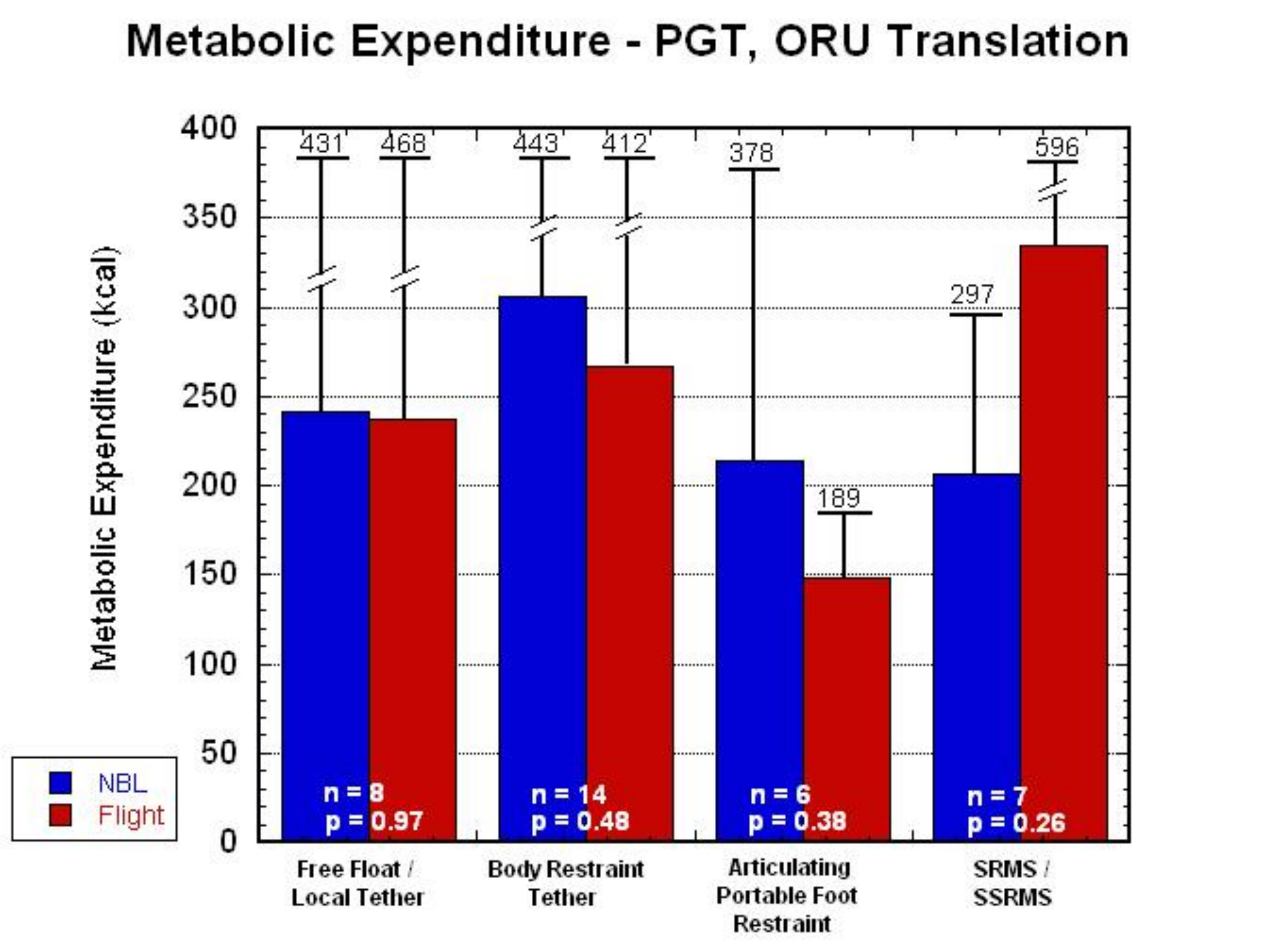
O_2 Depletion

Activity	Met Rate (kcal/hr)
Resting	77
Walking	140
Swimming	500
Tennis	500
Jogging	800
Walking up stairs	1100

Representative Met Rates


Average Metabolic Rates - PGT, ORU Translation
Metabolic Rate (kcal/hr)
400
350
300
250
200
150
100
50
0
26
38
39
27
12
25
93
66
n = 8
p = 0.09
n = 14
p < 0.01
n = 6
p < 0.01
n = 7
p = 0.32
NBL
Flight
Free Float / Local Tether
Body Restraint Tether
Articulating Portable Foot Restraint
SRMS / SSRMS
All restraint methods combined, p = 0.03. Error bar represents standard deviation.

Results



All restraint methods combined, $p = 0.92$. Error bar represents standard deviation.

Results

- In general metabolic rates tend to be higher in NBL than in flight
  - Restraint method dependant
  - Significant differences between the NBL and flight for BRT and APFR (buoyancy effects)
  - No significant difference between NBL and flight for free float and SRMS/SSRMS operations

- The total metabolic energy expenditure for a given task and for the EVA as a whole are similar between NBL and flight
  - NBL metabolic rates are higher, but training EVAs are constrained to 5 ½ hours
  - Flight metabolic rates are lower, but the EVAs are typically an hour or more longer in duration

- NBL metabolic rates provide a useful operational tool for flight planning

- Quantifying differences and similarities between training and flight improves knowledge for preparation of safe and efficient EVAs

Conclusions

Questions?

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